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THESIS

AN INVESTIGATION INTO THE USE OF 3D SCANNING AND PRINTING TECHNOLOGIES IN THE NAVY COLLABORATIVE PRODUCT LIFECYCLE MANAGEMENT

by

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December 2013

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13. ABSTRACT (maximum 200 words)

The Navy Collaborative Product Lifecycle Management (CPLM) is notional for the construction of scenarios for this thesis. Theoretically, CPLM works with suppliers to design, manufacture, and distribute parts and equipment required for routine operations. However, there are some issues with this, including the length of time required for designing parts and supply chain interruption, which means that there is a need to improve the process. The option for improvement explored in this research is the use of three-dimensional (3D) scanning (3DS) and printing (3DP) technologies, which respectively offer the ability to generate a computerized shapefile from a 3D object and then to transform this shapefile back into a physical object. 3DS and 3DP technologies are widely used in product design, as it enables rapid production of prototypes, including functional prototypes. 3DP can also be used for rapid manufacturing on a small scale (such as production of spare parts) or large scale (especially using lost-wax casting).

These technologies do have a potential benefit for the Navy's CPLM process, because it could help solve problems like supply chain disruption, immediate replacement of parts, and the length of the product development lifecycle. However, 3D technologies can be expensive, and in some cases may not be accurate enough for use. In this research, three distinct scenarios for implementation of 3D technology in the CPLM cycle are examined, including prototyping, small-scale shipboard manufacturing, and large-scale rapid manufacturing.

The findings of the research suggest that at the present time the use of 3DS and 3DP technologies is best suited to the design stages of the research, although the rapid manufacturing application also has promise. The shipboard application, although it would resolve a supply chain problem, is too expensive and complicated to be effective at this time.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	three-dimensional
3D LST	three-dimensional laser scanning technology
3DP	three-dimensional printing
3DS	three-dimensional scanning
CAD	computer-aided design
CBA	cost benefit analysis
COTS	commercial off-the-shelf
CPLM	Collaborative Product Lifecycle Management
CT	computed tomography
DoD	Department of Defense
FDM	fused deposition modeling
LT	lieutenant
MEMS	microstereolithography)
MRI	magnetic resonance imaging
NPV	net present value
PLM	product lifecycle management
R&D	research and development
SLA	stereolithography
SLS	selective laser sintering

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I. INTRODUCTION

Three-dimensional (3D) scanning (3DS) and printing (3DP) technologies are some of the most exciting new technologies for product design, development, and manufacturing. However, they have not yet been fully utilized within a potential Collaborative Product Lifecycle Management (CPLM) environment in the Navy. This research seeks to examine whether these technologies should be used and in what scenario their use could be beneficial, as well as to determine the costs and risks involved in the implementation.

A. STATEMENT OF THE PROBLEM

The Department of Defense (DoD) has been increasingly scrutinizing the budgets of the Armed Forces, compared to past generations. Both the budget scrutiny and the unchanged global threat forces the U.S. Navy to explore new approaches for reducing costs while maintaining both its current force structure, as well as its capabilities and mission readiness. The Navy spends an enormous amount of its budget on the ship maintenance process. With that in mind, previous research has theoretically quantified significant cost and time saving benefits that resulted from the integration of 3DS+3DP technologies with the Navy's ship maintenance process. The implementation of any new technology into an existing infrastructure inherently carries high technological risks, which translate to high failure rates and wasted sunken costs. To mitigate these high risks additional research is warranted to validate findings of previous research prior to moving forward with the implementation of CPLM+3DS+3DP into the ship maintenance process. Currently, there is no CPLM process in active use in the U.S. Navy. This research is an exploratory, counterfactual study that examines how, if a CPLM approach were to be used, 3DS and 3DP technologies could be effective.

B. PURPOSE STATEMENT

This study intends to further the research of the previous thesis work of Lieutenant (LT) Nate Seaman (2007), entitled "The Use of Collaborative and 3D Imaging

Technology to Increase Value in the SHIPMAIN [ship maintenance] Environment of the Fleet Modernization Plan 2007."

This research aims to review the latest developments and practices of 3DS and 3DP technologies and how the tools are being applied in the commercial/government sector in industrial areas similar to ship maintenance. The study will examine the potential cost/benefits resulting from the application of these technologies to determine where the technologies might be incorporated into the Navy's maintenance program to achieve cost/benefits for its ship maintenance process. The study will include an intense literature review of 3DP technology to assess levels of readiness and risks associated with the new technology.

C. RESEARCH BACKGROUND

The fiscal realities of the DoD have caused a more close examination of the budgets of the armed services. Global threats are unaffected by the financial situation of the U.S., so the force structures of the U.S. Armed Forces must stay the same to meet the current threat environment. Nonetheless, the DoD continues to scrutinize the armed services' budgets to influence them to reduce costs under current global threat conditions while still meeting their current missions. In 2005 and 2006, the DoD spent $59 and $72 billion respectively in maintenance alone. This represents an appalling growth rate of 22 percent in the course of one year (Siemens PLM Software, 2010).

Cost-cutting objectives and acquisitions practices optimization during challenging economic times force the U.S. Navy to look for ways to improve inefficiencies in maintenance, acquisitions, and outfitting processes to find areas in which to reduce costs all the while maintaining capabilities and mission readiness. The Navy realizes that one of its areas of high cost is related to the ship maintenance process. Although CPLM is one potential choice for reducing costs, to date this has not yet been implemented. To meet cost savings and readiness objectives, the Navy needs to analyze the costs and benefits of creating a CPLM process and embedding 3DS and 3DP technologies into the Navy's processes for ship maintenance. Various commercial sectors already use these tools to cut cost with a great deal of success. During economic difficulties, the American

ship building industry, looking to improve their profit margins, managed to do so from the integration of 3DS and 3DP technologies into their the industry processes for research and development (R&D) and maintenance through the creation of valuable R&D prototypes and products. The experiences of these companies can provide a baseline, and empirical data from which to estimate cost/benefits for this study. However, this study only addresses the integration of 3DS and 3DP into CPLM, building on previous work that provided a foundation for a putative CPLM process.

3DS and 3DP are relatively new technological developments. The 3D scanner scans an object and builds a detailed model of its physical characteristics (Yu, Lu, & Luo, 2003, p. 17). Its counterpart, 3DP, uses a computer-aided design (CAD) model or other computer-generated model to create a physical object (Gibson, Rosen, & Stucker, 2009, p. 7). The 3D printer, which uses stereolithography (aka SLA) or another process to build an object based on successive layers of a plastic or metal substrate, is useful for rapid prototyping, or even for production of pieces of some assemblages for repair or retrofitting. 3DS and 3DP are becoming increasingly common in product design and manufacturing processes, as it reduces the time required to build models and allows for limited manufacturing capabilities (Parsons, 2009, p. 107).

1. The Potential for 3D Technology

Authors such as Gibson, Rosen, and Stucker (2009), Parsons (2009), and Yu, Lu, and Luo (2003) demonstrate the technical uses of 3DS and 3DP technologies and explore how the technologies are used in the product design process. There is an existing body of research that discusses the technologies and their uses. One review of the technology in 2006 found various uses already in place, including manufacturing processes (Dimitrov, Schreve, & de Beer, 2006, p. 136). The use of rapid prototyping through 3DS and 3DP has a number of implications for the process of product design and manufacturing. For example, Reiter and Major (2011) found that rapid prototyping processes assist in visualizing motion and interaction within designs, enabling an improved mechanical design process as well as reducing the time required for development of a machine. A review of the literature shows 3DP and rapid prototyping to be part of an efficient process

of product design for various products, such as rotary switches (Vinodh, Selvaraj, & Praveen, 2012, p. 380). The use of 3DS and 3DP, according to Vinodh et al. (2012), was particularly useful for implementing an agile product development cycle for this product. 3DP is also increasingly flexible; although most 3D printers currently use various polymers (or in some cases metal), materials such as rapid-setting Portland cement have also been used (Gibbons, Williams, & Purnell, 2010, pp. 287–288). However, the use of rapid prototyping using 3DS and 3DP go beyond simple physical modeling of the material and process. For example, the rapid prototyping process can be used to predict total product lifecycle costs, allowing for analysis of the environmental impact of the finished product (Fiksel, & Bakshi, 2010, p. 1).

The existing literature on 3DS and 3DP makes it clear that evaluation of these technologies for military product development is well grounded and implementing them could potentially bring substantial benefits. It is clear that there are military applications for this technology. For example, Campbell, Bourelle, and Gibson (2012, p. 256) note that 3DP is used to manufacture polymer parts for military jets, among other uses. However, there have been few detailed studies performed regarding 3DS and 3DP technologies and its use in the U.S. Navy. There is one previous thesis available through the Naval Postgraduate School. Nathan Seaman addressed the use of 3DP technology in the Fleet Modernization Program. This thesis intends to reinforce Seaman's thesis as secondary research (2007). However, given the changes in technology and cost of 3DS and 3DP, it is likely that the results of a cost-benefit analysis (CBA) would be different at the present time. Given this situation, the gap this research is intended to fill is the direct application of modern technologies to the current situation in the Navy's CPLM process and determination of the costs and benefits of the technology.

2. The Role of 3D Technology in SHIPMAIN

Because of the rapid prototyping and production capabilities offered by these technologies, the technologies could potentially create substantial cost and time savings in the Navy's ship maintenance process. The findings resulting from this research could be expanded to other agencies that engage in the same type of research and product

development. Based on this, we expect that this research would serve as a general interest analysis of 3DS and 3DP technological readiness and uses.

D. RESEARCH QUESTIONS AND HYPOTHESES

The study looks for answers to the following important questions in order to determine the potential cost/benefits.

- How does the commercial/government/defense sector integrate 3DP+3DS in its industrial maintenance processes in order to achieve maximum cost/benefits?
- Can 3DP be integrated into a putative CPLM+3DS technology suite used in its ship maintenance process to achieve additional cost/benefits?
- Can the CPLM+3DS+3DP technology suite provide a greater ROI than realized from current methods used in the ship maintenance process?
- Can the use of CPLM+3DS+3DP improve the Navy's overall mission readiness?

Quantitative research conducted by Seaman (2007) has revealed that CPLM+3DS technologies could have significant impacts upon the ship maintenance process. According to LT Seaman:

> Analysis of this study reveals the significant potential value that 3D laser scanning and PLM technologies have to offer maintenance and modernization efforts for U.S. Navy warships. Cost savings are the most apparent and profound benefit potentially offered by 3D data capture and PLM tools.

E. ARRANGEMENT OF THE STUDY

There are five key chapters in this study. The first chapter (Introduction) has offered insight into the reason for undertaking the research as well as outlined the questions that will be asked. Chapter II (Literature Review) provides a detailed introduction to 3DS and 3DP technologies and reviews case studies and other literature showing how these technologies can be used. Chapter III (Methods) introduces the two-stage methodology used in the research, which integrates first scenario-based simulation and then CBA. Chapter IV (Findings and Discussion) presents the outcomes of the research and then discusses it critically. Chapter V (Recommendations and Conclusion)

concludes the study and offers recommendations for further research into the area, as well as recommendations for implementation of 3D technologies into the CPLM process.

II. LITERATURE REVIEW

This chapter presents a comprehensive literature review on the use of 3DS and 3DP technologies in industry. 3DS and 3DP technologies have been widely discussed in the literature in terms of its development and experimental applications, but it has not been widely discussed in a military product development context. Because of this, the current research will draw primarily on the existing literature in experimental and industrial contexts. The goal of the literature review is to provide a strong basis for analysis of the use of 3DS and 3DP technologies in the U.S. Navy's CPLM process, by examination of the technologies in similar (though not identical) contexts. Ultimately, it will explain commercial, government, and military approaches to using 3DS and 3DP technologies and analyze the costs and benefits associated with the project.

The literature review was prepared using an initial comprehensive survey of the existing literature, followed by targeted selection of literature that directly addressed the topic in question. The focus of the literature review was on the selection of peer-reviewed literature, conference publications, and academic books, which are generally preferred in research because they have been previously screened for reliability and validity (Fink, 2009). In some sections, additional information has been selected from military-specific sources (although these are not peer-reviewed), as is appropriate for specialist applications or sectoral concerns (Fink, 2009). The literature review is focused on describing and explaining specific aspects of the research problem. It begins with a discussion of the technologies that are at the center of this research, which include 3DS and 3DP. The uses, costs, and benefits of the 3DS and 3DP technique are then studied, focusing on various key uses of the techniques (such as rapid prototyping and various production methods), the limitations of the techniques, and the use of the technologies in the military. The final key topic is CPLM, and in particular the U.S. Navy collaborative product lifecycle process. This piece of the research is intended to demonstrate how 3DS and 3DP may already be used. It also explores some of the ways that the technologies

might be used. The literature review is then used to build a conceptual framework that will be used to understand the problems of this research project, which ties into the next chapter (the methodology discussion).

A. TECHNOLOGIES

There are two key technologies at the heart of this research, 3DS and 3DP. Although these technologies address a similar regime of product design, they were developed separately and use distinct approaches to the problem of on the one hand creating a stored image from a physical object 3DS and on the other hand creating a physical object from a stored 3D image. In this section, a brief overview of the history of these technologies, technologies, their development, and high-level technical summary of their details is provided, along with insight into their capabilities and limitations. A full description of the technical implementation of these technologies is outside the scope of this research, but this section (as well as the Limitations section) does discuss some of the technical issues that might be encountered.

1. 3D Scanning

3DS is an image capture process that capture surface information from a 3D physical object, including dimensions, surface patterns and textures, and other aspects of the object (Vaughan, 2012). This information is then converted into a digital mesh that can be manipulated and changed using a 3D modeling interface (Vaughan, 2012). There are a variety of different form factors for 3D scanners, including contact scanners and non-contact scanners. As could be expected, the difference between contact and non-contact scanners is that contact scanners require physical contact with the item being scanned, while non-contact scanners use a chamber or other enclosed area to scan the object (Vaughan, 2012). Non-contact scanners may be active (or radiation-emitting) or passive (relying on reflected light radiation to detect objects and contours) (Vaughan, 2012). A typical form factor for a contact scanner is a tracing pen, which is used to connect information along a particular axis (Vaughan, 2012). In contrast, non-contact scanners may be small desktop units, medium-sized units, or units that are substantial enough to scan a person or even larger items in (Vaughan, 2012).

3D scanners are commonly used for a variety of different applications, including medical imaging, animation and game imaging, and product design and development (Vaughan, 2012).

In some cases, these may be built on older technologies. For example, x-ray computed tomography (CT) scanners produce 2D slices of a given object, which can then be combined in order to create a 3D image (Vaughan, 2012). One of the earliest applications of 3DS was actually scanning of the human form in order to refine fit of clothing designs, based on its offering of extremely accurate anthropometric measurements (Paquette, 1996). However, there have been considerable advances since Paquette's (1996) report of laser 3DS used in clothing design. Although 3DS may still be used for anthropometric imaging, it is also commonly used in industrial design today (Vaughan, 2012).

The development of 3DS was not without its challenges, especially challenges regarding accuracy. For example, 3DS for facial recognition faced substantial challenges in becoming accurate enough for reliable use (Boehnen & Flynn, 2005). The authors noted that at the time, there was wide variation in the accuracy of commonly used 3D scanners, and that some scanners required special techniques or calibration prior to their use in order to avoid patchy or unresolved appearance (Boehnen & Flynn, 2005). This issue has been resolved somewhat in higher-quality scanners of modern construction, however (Vaughan, 2012). Modern 3DS for facial recognition is significantly more accurate, using motion capture and tissue depth markers to provide simplified and more accurate results (Huang, Chai, Tong, & Wu, 2011). However, there are still issues with smaller-scale scanning (Huang et al, 2011), which could influence the use of 3DS for very finely detailed items.

The technological development of 3DS is an ongoing process. One particular challenge that has been overcome relatively recently is the use of 3DS for translucent objects, which posed a problem due to the incidence of subsurface scattering of the transmitted radiation in active non-contact scanners (which have been most frequently used) (Chen, Lensch, Fuchs, & Seidel, 2007). Subsurface scattering results in a poorly constructed image because of inadequate range estimation (Chen et al., 2007). In order to

resolve this problem, Chen et al. (2007) used a process of polarization-difference imaging, and then captured the image using structured light scanning (which uses a projection of light radiation onto the object and then measures the deformation caused in order to detect surface, contours, and dimensions (Chen et al., 2007). This allowed for more accurate scans of translucent objects. However, other technical challenges have also arisen with the development of different formats for scanners, such as the use of structured light scanners in situations where there are high levels of global illumination effects (Gupta, 2011). Global illumination refers to inter-illumination between object surfaces, such as reflection or shading (as opposed to direct lighting from the structured light used by the scanner) (Gupta, 2011). These aspects of illumination can pose a challenge to accurate scanning, and the reconstruction algorithms used by the scanner may not always eliminate them, leading to distortion of the image by the scanner (Gupta, 2011). Thus, even though the 3D scanner has been under development since the mid-1980s (Vaughan, 2012), there are still significant issues in image processing and light management that can influence how effective individual scanners are.

It is clear that not all the problems associated with 3D scanners are resolved. However, the technology has been becoming both cheaper and more accurate over time. For example, one study examined the accuracy and reliability of commercial off-the-shelf (COTS) scanning systems for measuring the microtexture (or microrelief) of agricultural soils (Aguilar, Aguilar, & Negreiros, 2009). The authors noted that this is an important characteristic of agricultural soils because it determines runoff and erosion among other behaviors. They used several non-contact 3D laser scanners bought on the commercial market in order to perform open scanning of agricultural plots (Aguilar et al., 2009). The authors found that the standard deviation of the residual was smaller for laser imaging and the traditional photogrammetry approach (indicating higher accuracy), and that resolution of 0.4mm for laser scanning compared well with resolution of 1.0 mm for photogrammetry (Aguilar et al., 2009). Thus, COTS 3D scanners selected was as or more accurate and high-resolution as the more expensive photogrammetry approach. This

has positive implications for the use of 3DS technology in product development, since it reduces the cost of implementation and reduces reliance on bespoke technology, increasing the ability to use COTS technology instead.

This improved accuracy is not absolute. For example, a study of 3DS of architectural objects noted that geometric accuracy is likely to be much higher than representation of surface texture, at least within that setting (Zalama, Gómez-García-Bermejo, Llamas, & Medina, 2011). The issue of surface texture is known from an informal survey to be a major limitation on the use of 3DP as well (Park, 2012), suggesting that this is a general issue in 3D design and production technologies.

Despite this limitation, Zalama et al. (2011) note that 3DS and image capture is still a highly effective approach for architectural objects, and that surface textures can be automatically applied by using still image capture and post-processing. In terms of product design (such as, in the case of the discussed paper, reverse product design), the accuracy and resolution of modern non-contact 3D scanners using a structured light technique is more than high enough to capture the required features of the 3D object in question, including surface textures, dimensions, lines, and other features (Peng & Sanchez, 2011). These images can then be used to create 3D virtual or physical models of the object, architectural region, or other scanned item that provide a visually and textually rich interaction experience (Adan, Xiong, Akinci, & Huber, 2011). Thus, even though 3DS is still a technology in the process of development, it has been shown to be effective in product imaging and design and is generally highly accurate and high-resolution.

2. 3D Printing

3DS may be used in conjunction with 3DP (though it may also be used independently). Like 3DS, 3DP is a technology in development, but it is also a technology in active use in the product development environment. 3DP can be defined as creation of a physical object from a geometry file or model stored in a computer using a process of accretion (or additive deposition) of materials on a substrate (which may itself be created by the printing process) (Evans, 2012). Commonly, the model the 3DP process

uses may come from the 3DS process, but it may also be created in a 3D modeling program such as Maya (Evans, 2012). There are a range of different technologies that may be used for 3DP, which have varying levels of complexity and cost associated as well as different levels of accuracy and materials that the process can handle (Evans, 2012). Some examples of 3DP technologies include:

- Extrusion (fused deposition modeling or FDM), which primarily works with thermoplastics and some metals
- Granular deposition (such as selective laser sintering (SLS) and inkjet head 3DP), mostly used with plaster
- Light polymerization (such as SLA and digital light processing or DLP), which primarily work with polymers and resins (Evans, 2012)

In general, the light polymerization techniques are currently the most advanced and can achieve the finest levels of detail in the printed object (Evans, 2012). It is important to note that although most of the printing processes cannot handle metals or other materials, it is a trivial process to use lost wax casting or other molding techniques to create molds in order to replicate the product in other materials (Evans, 2012). However, there are also some techniques, such as functionally graded materials, that can be used to produce composite or layered materials in the same printing, increasing material flexibility (Erasenthiran & Beal, 2006).

The process of defining a 3DP process can be conceptualized in five stages, where various key decisions are made based on the intended purpose and outcome of the process (Utela, Storti, Anderson, & Ganter, 2008). The first stage, powder selection, is the stage at which the material that will be printed is made; as Utela et al. (2008) note, any material can theoretically be used as long as it works with the deposition method chosen. Powder formulation involves a number of choices, ranging from particulate size (which can be smaller than five microns to larger than 20 microns) to the inclusion of various additives and other materials such as lubricants, adhesives, and fiber additions (Utela et al., 2008). The size of the particle chosen determines whether the powder is deposited wet or dry, with larger particles enabling dry spread; however, particles can also be of mixed size, offering multiple advantages. The third decision to be made is how the powder is to be deposited, although as Utela et al. (2008) noted, that is a decision that

is more commonly made by the 3D printer manufacturer. Specifically, there are commonly only one or at most a few deposition techniques made available by any given printer. However, the user of the printer can control what binders are used for the particles (as well as other additives and fibers), and different binders offer different characteristics (Utela et al., 2008). The printing liquid must also be formulated in order to ensure appropriate deposition of the materials (Utela et al., 2008). The final stage is determining how the powder and binder interact, which can often be a process of trial and error (although there are some known rules and combinations that can be taken into account) (Utela et al., 2008). In many cases, as Utela et al. (2008) noted, there is no particular need to go through this entire process, as standard printing materials may fulfill requirements (particularly for situations like printing 3D simulation pieces for modeling); however, the option to create one's own deposition material is available, and it can be used to dramatically increase the flexibility and utility of 3D printed materials (Utela et al., 2008). Thus, even if the designers themselves do not use this detailed process, it is important to note that it is available to them should it become useful.

One of the most important uses of 3DP technologies in the industrial environment is rapid prototyping. Rapid prototyping can be done in a number of different ways, including 3DP of various types, hand-construction or machining of models, virtual models, and other approaches (Chua, Leong, & Lim, 2010). In general, 3DP is used as a fabrication process rather than a virtual process (Chua et al., 2010). Fabrication processes can involve additive processes (where the physical model is built using accretion or addition of material), subtractive processes (where a stylus or other carving mechanism is used to construct the model from a solid block of material), and formative processes (which use pressure to form a shape or mechanism from a block of pliable material) (Chua et al., 2010). Figure 1 shows the process chain for the rapid prototyping process as generalized by Chua et al. (2010). This cycle does not, however, take into account issues like customer input or testing; a more complete model of the product life cycle and the role of rapid prototyping is available below.

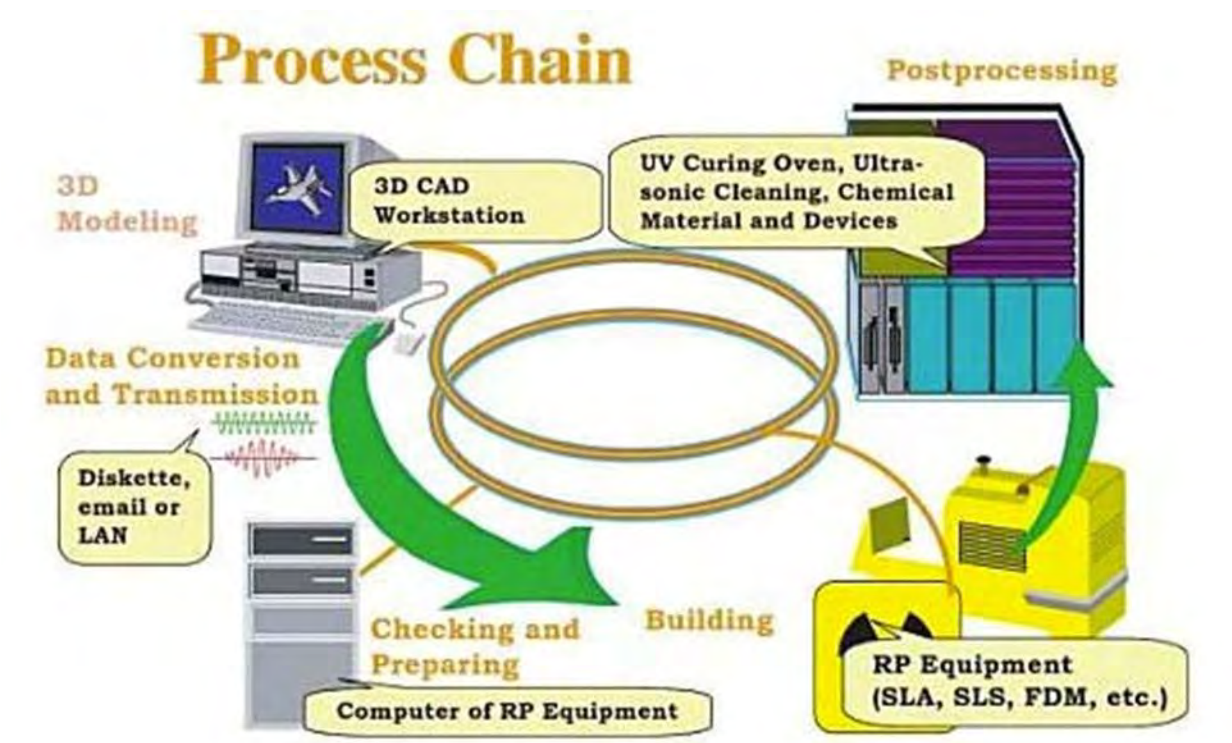

Figure 1. The rapid prototyping process chain (from Chua et al., 2010, p. 27)

SLA has been used for rapid prototyping, or the creation of functional objects for product design and handling, since at least the late 1980s (Jacobs, 1992). However, it is still not an uncomplicated approach. The most superficial problem with the process is that the 3D model on which the printed object is based must be accurate (or in other words, there is a garbage in, garbage out problem) (Chua et al., 2010). There is also a limitation on materials that can be used, although as noted above molds can be made to extend the range of materials (Evans, 2012) and there are an increasing number of materials that can be used with SLA printers (Melchels, Feijen, & Grijpma, 2010). Regardless, SLA is one of the most commonly used 3DP techniques, due to its high level of accuracy and resolution that it can achieve as well as some of the newest developed materials, which include porous and biodegradable materials (making it ideal for customization of biomedical devices) (Melchels et al., 2010). Microstereolithography (aka MEMS), which involves the fabrication of very small devices such as microcontrollers or microfluidic devices (with sizes as small as 1 μm), offers some of the most advanced rapid prototyping

capabilities (Rosen, 2008). Thus, SLA offers a means of rapid prototyping that is both highly accurate and high resolution and capable of producing devices that are very small (though they do not have to be), offering a highly flexible and advanced technology for rapid prototyping.

A substantial amount of the research that has been performed on rapid prototyping with SLA is directed to biomedical engineering, which may not be directly applicable in this instance. However, this body of research does offer insight into some of the remaining challenges with 3DP generally and SLA particularly. For example, one article discussed the problem of creating 3D models from existing imagery for SLA in the context of fabricating physical models from medical images (Vaezi, Chua, & Chou, 2012). Vaezi et al. (2012) examined the use of medical imaging technologies like 3D ultrasound, CT, and magnetic resonance imaging (MRI) in order to determine which of these technologies had sufficient resolution and accuracy to produce medical models. In this research, a 3D model of a fetus was generated (because of the commonplace use of ultrasound in generating images without harm to fetuses), which the authors found had sufficient accuracy and resolution (Vaezi et al., 2012). Another study identified a particular problem in the application of SLA to the generation of replacement parts for freeform-surface parts (for example, a turbine blade) (Li, Wu, Tang, & Zhao, 2011). Li et al. (2011) noted that although SLA was attractive because it was less expensive than alternative methods, it had problems especially when working with ceramic additive materials (which tended to develop surface cracks), which meant that for some industrial applications the use of SLA was not considered to be appropriate. Li et al. (2011) partially resolved this problem by changing the composition of the material used for SLA, but this still shows that not all problems with SLA have been resolved. This means that although it has a long history of use for rapid prototyping, the effectiveness of this approach cannot yet be accepted fully.

B. COSTS AND BENEFITS OF 3D SCANNING AND PRINTING

There are a number of benefits of 3DS and 3DP that can be found within the literature. Many of these have to do with the use of the technologies in the rapid

prototyping process, which enables the use of 3DS and 3DP technologies for product design and development. However, there are also other benefits to the product designer and lifecycle, including the composition of complex materials (potentially unavailable to the designer) and the use of 3DP for rapid manufacturing. However, these techniques are also associated with various costs and limitations, which are also discussed within this section of the chapter. This is also a somewhat conflicted area of research, as discussed below. The cost of 3DS and 3DP technologies has been changing rapidly, particularly at the lower end of accuracy. However, while inexpensive desktop machines are available, the more precise machines are still relatively expensive. Thus, the literature does have a conflict in terms of the cost reflected, which is discussed within the body of the research. This section of the literature review offers support for the development of the conceptual framework, presented below.

1. Rapid Prototyping

Perhaps the most important use of 3DS and 3DP is rapid prototyping. Rapid prototyping is the process of generating a prototype (or a mid-process design) for physical inspection and manipulation during the design process (Bak, 2003). Rapid prototyping does not always, however, allow for exploration of the physical properties of the part, due to material limitations (Bak, 2003). One example of the process of rapid prototyping and its uses is the reproduction of a Chinese historical artifact, a porcelain teacup (Feng & Jiang, 2012). This reproduction was performed in order to create a larger number of the teacups in order to place on display, offering the public a chance to view the item without endangering the original (Feng & Jiang, 2012). The authors used 3DS to create a point cloud image of the historical artifact, and then used the Range Viewer and RapidForm XOR CAD drafting packages to manipulate the generated point cloud in order to prepare it for reproduction (Feng & Jiang, 2012). They then used a 3D Systems Projet 5000 3D printer, with liquid photosensitive resin, in order to create multiple copies of the teacup, which had a high fidelity in terms of dimensions and surface design to the original (Feng & Jiang, 2012). Obviously, the materials and items designed within the naval product lifecycle process are far more complicated than teacups, but Feng and

Jiang's (2012) straightforward explanation of the process shows the basic functionality of the rapid prototyping process as well as its capabilities for reverse engineering and high-fidelity reproduction of existing objects.

An application of rapid prototyping perhaps more relevant to the naval product lifecycle is discussed by Budzik (2010), who examines the creation of aircraft engine blade models using rapid prototyping techniques. This study also identifies some of the challenges of effective rapid prototyping. The author used 3D-CAD software in order to generate a 3D model of an aircraft engine blade, and then examined the layer thickness of the model as created by two different techniques (FDM and SLA) (Budzik, 2010). Budzik (2010) found that the orientation of the model was relevant to the accuracy of layer thickness as produced by the 3DP techniques; while matching the orientations of the z axis of the blade and device showed a high level of accuracy, matching the y axis of the blade to the x axis of the device substantially reduced the layer thickness accuracy (Budzik, 2010). This is not immediately obvious from the software or directions for development of a 3D rapid prototype model, and may not be the same for all types of device (Budzik, 2010). Thus, there is considerable skill involved in generating a rapid prototype model, even using the facilities of the 3DS and 3DP tools.

2. 3D Printing and Complex Materials

One of the major benefits of 3DP is that it can be made to work with complex materials, although by default the materials it uses (such as polymers and starches) are simple. One example is the use of 3DP to fabricate Ti3SiC2 (titanium silicon carbide)-based ceramics (Nan, Yin, Zhang, & Cheng, 2011). These ceramics are highly valued in high-temperature and electronic applications because of characteristics such as high oxidation resistance, low electrical resistance, and low density; however, it also has low strength and fracture toughness, making it difficult to manufacture. Nan et al. (2011) found that using 3DP, it was possible to create complex shaped titanium silicon carbide components. These components often cannot be manufactured using traditional techniques, because the low fracture toughness and strength of the base material makes it difficult to use cutting or shaping techniques that might otherwise be used in ceramics

manufacture (Nan et al., 2011). Thus, the ability to manufacture components from titanium silicon carbide using a combination of 3DP (to produce preforms of arbitrary shape) and aluminum melt capillary infiltration (to complete the reactive process) represents a significant improvement in complex materials availability (Nan et al., 2011)

Another type of complex material allowed by the use of 3DP is metallic cellular material (Williams, Cochran, & Rosen, 2011). As Williams et al. (2011, p. 231) explain, metallic cellular materials are "metallic bodies with gaseous voids interspersed through the solid body… [offering] high strength accompanied by relatively low mass." However, though these materials are known to be useful in design areas, they are not yet readily manufactured or available for use because of the complexity of manufacture; instead, only a few metallic cellular materials are available, which are not always appropriate for a given application (Williams et al.., 2011). Williams et al. (2011) developed a process that involved printing solvents onto metal oxide ceramics, and then sintering the materials together. They report that this created a metallic cellular material with 270-µm shell thickness, offering improved accuracy for some applications (Williams et al., 2011). The generation of one such process suggests that this process could be extended to create other custom metallic cellular materials, extending the ability of the designer to utilize these complex materials in their designs. Thus, one of the major benefits of 3DP for the product design process is enabling the use of complex materials.

3. 3D Printing as a Production Mechanism

One of the potential benefits of 3DP is that it can be used, at least in some cases, as a rapid production methodology. Bak (2003) noted that at the time, rapid production (or production using 3DP as a means of generating products without the complicated setup of job- based production methods) was still not very strongly in use. This was due to the high volume that was thought necessary for production to be economically feasible (Bak, 2003). However, this was an area of rapid development through the 2000s. One approach that has been used for rapid production using 3DP is not to use the 3D printers themselves to produce objects, but instead to use the 3D printed prototype object to generate a mold for a standard production line (Bassoli, Gatto, Iuliano, & Violante,

2007). This process, known as rapid casting, is particularly useful for producing objects in materials that are difficult to produce with 3D printers, such as some metals, glass, Styrofoam, or composite materials (Bassoli et al., 2007). This technique can also be used to increase the production volume for 3D printed materials (Bassoli et al., 2007). A recent review of 3DP for casting applications shows some considerable development in this area, including development of new deposition materials such as composites and starches that can be used to generate different types of molds or forms (Singh, 2010). The most important benefit of using 3DP as a shortcut for mold-based manufacturing is that it allows for the bypassing of the metal die production stage, which can take as long as two to six months for some complex molds (Sing, 2010). This increases the speed with which mold-based casting can be undertaken substantially, since 3D printers can be used to generate a mold almost immediately (Singh, 2010). It also significantly reduces the cost of tooling for small-batch or job-based manufacturing processes, allowing for economic production runs of as few parts as required for the production process (Singh, 2010). Thus, the use of 3DP as a production process has considerable benefits. These benefits can be extended given that 3DS can be used to generate a computer model of the object to be printed in the first place, enabling rapid reproduction of existing items or those that require minor modification (Singh, 2010).

There are a number of manufacturing applications that are relevant to the military production process. 3DP has been used as the basis for manufacturing parts for aircraft, and there have been specialist alloys created for this purpose (Dimitrov et al., 2006). In particular, a manufacturing process for creation of parts using Ti3SiC2 (titanium silicon carbide) using a standard scanner has been used to generate parts for applications such as aircraft engines and standard diesel engines (Dimitrov et al, 2006). Other manufacturing processes allow for the creation of rubber parts such as wheels and gearshift boots (Dimitrov et al., 2006). These processes are useful not just because they allow for prototyping of new equipment, but because they also allow for field parts replacement of parts that are not sturdy or are otherwise difficult to supply. However, this is one of the higher-accuracy requirements of 3DP and not all equipment may be capable of achieving this level of accuracy (Dimitrov et al., 2006).

One of the most obvious uses of 3DS and 3DP as a production mechanism is in the area of mass customization, or creation of similar but distinct items based on specified changes (such as through a template or design) (Reeves, Tuck, & Hague, 2011). Reeves et al. (2011) explored the use of 3DP as a means of generating small physical items based on character specifications from a massively multiplayer online role-playing game (MMORPG) as well as other sources. The availability of multiple materials (such as polymers and metals) as well as the ability to easily retool production modeling for the changes in design mean that it is highly useful for this application (Reeves et al., 2011). Although Reeves et al. (2011) explored this application in a relatively minor consumer context, it would also be applicable in product design contexts; for example, it could be used to present multiple modifications of a single design for testing and evaluation.

While the 3D printed object can be used to make an impression for lost-wax or investment casting (as noted above), it can also be used directly to print functional parts using plastic or metal materials. Some of the earliest envisioned uses for 3DP involved direct production of functional prototypes and usable parts, as well as the integration of 3D parts into the production process (Sachs, Cima, & Cornie, 1990). While Sachs et al. (1990) only had access to polymer powders, there has been much more R&D of the technique since this early project that allows for more flexible use.

One of the most useful developments in this area is the development of functionally graded materials, which are “a form of composite where the properties change gradually with position [and which] can be tailored to meet specific needs through the utilization of composite components” (Erasenthiran & Beal, 2006, p. 103). These composite materials offer substantially more flexibility for production of functional parts (Erasenthiran & Beal, 2006). For example, parts can be manufactured using a metal core and polymer coating (as might be required for adjusting fit of a given piece. Functionally graded materials can be designed to offer different characteristics, such as strength, resistance or toughness, temperature resistance, or other features depending on the needs of the specific part (Erasenthiran & Beal, 2006). Figure 2 shows how functionally graded materials can be used to provide different physical characteristics in the same part.

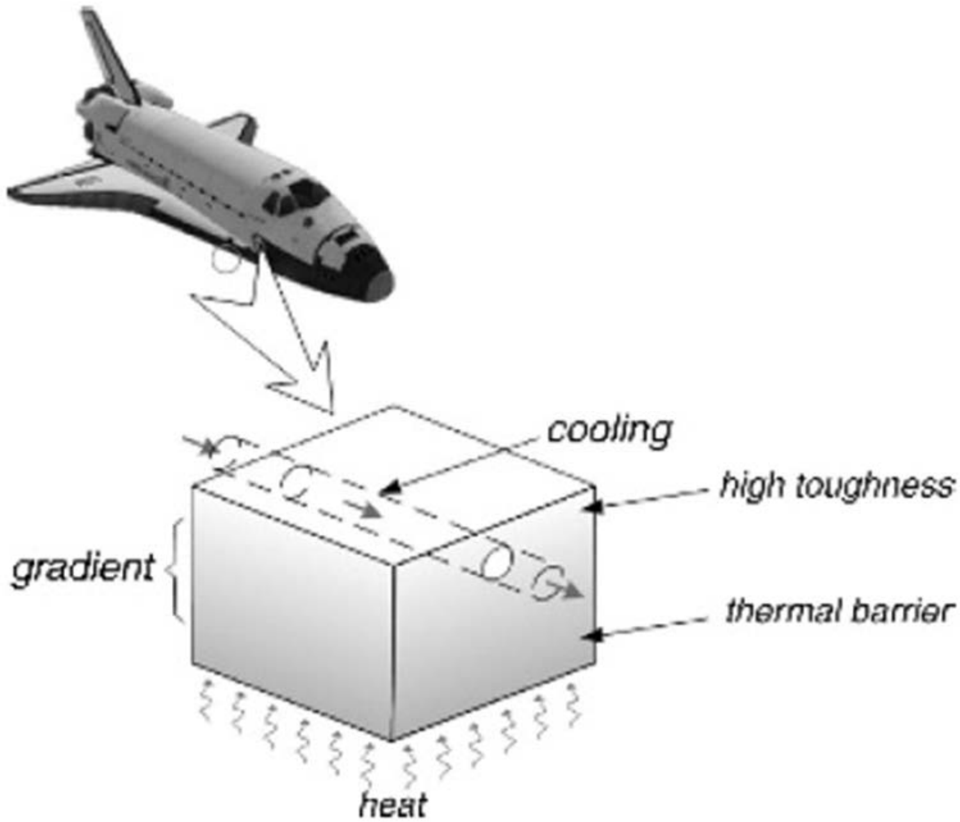

Figure 2. A single part with different elements requiring different physical characteristics (from Erasenthiran & Beal, 2006, p. 104)

According to Eresenthiran and Beal (2006), there are several processes that can be used to create functionally graded materials, including constructive and transport processes and rapid manufacturing processes. These processes are shown in Figure 3. According to the authors, constructive and transport processes were most common at the time (Erasenthiran & Beal, 2006). There is no current evidence about the development of rapid manufacturing processes directly in the literature, though increasing popularity of these methods could suggest that they are more common. In terms of design, functionally graded materials begin with the use of CAD to design the part, as is standard; the main difference in their use is in the choice of material methods, as described by Utela et al. (2008).

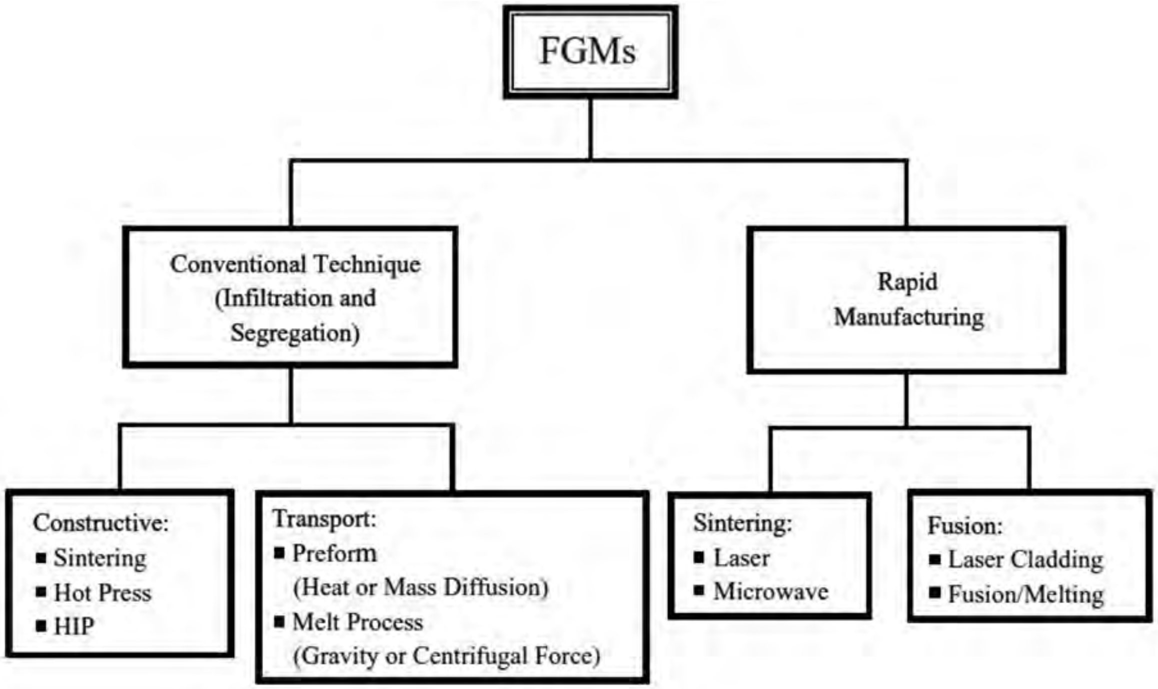

Figure 3. Various methods of production for functionally graded materials (from Erasenthiran & Beal, 2006, p. 105)

3D printed materials do have certain physical limitations in their use, including limitations having to do with fluidity and plasticity as well as time required, materials strength, porosity, and fragility (Bourell, 2006). For example, sintering (or "time-dependent consolidation of a porous medium (Bourell, 2006, p. 84)") is much faster for polymers than for metal or ceramics, making these materials more or less practical for functional parts production. Thus, the choice of materials and composites is fundamental to the development of functional parts (Bourell, 2006). In addition to the development of composites and functionally graded materials (as discussed above), there are a number of methods that can be used to improve the characteristics of materials. For example, infiltration (or filling of the SLS or 3DP part with a lower-density liquid metal) can be used to reduce porosity of the produced part (Bourell, 2006).

Ultimately, this creates a full-density part that can actually be used as a functional part even from an SLS-produced polymer output (Bourell, 2006). The outputs of this process are shown in Figure 4. However, parts may still face a number of challenges in

use, including problems with tensile strength, stiffness, fatigue and fracture problems, and other physical issues (Bourell, 2006). This can affect the mechanical utility of the part, including effects on the durability and reliability of the part (Bourell, 2006). Thus, 3DP cannot be used for all production of functional parts, particularly those that undergo unpredictable or constant physical stresses. However, it can still be used to produce parts that are functional within the material and engineering boundaries of 3DP.

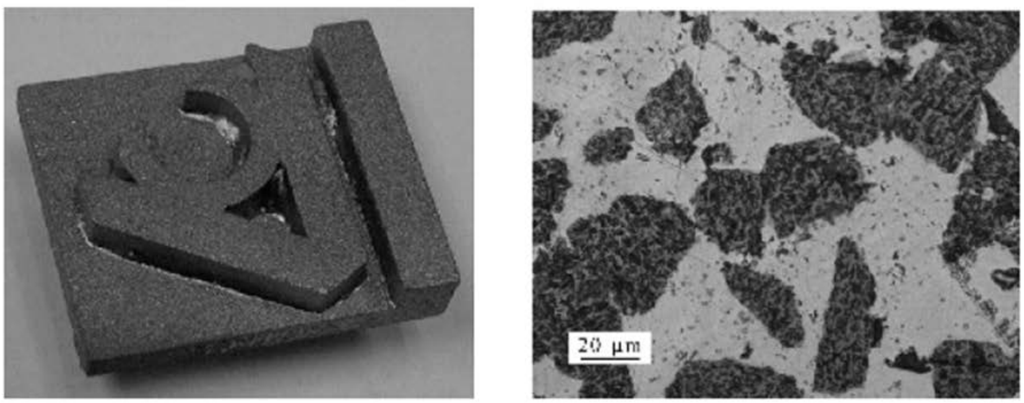

Figure 4. Silicon-infiltrated silicon carbide (SiC2) preform initially produced using SLS (from Bourell, 2006, p. 94)

4. Use of 3D Scanning and Printing in Military Applications

The 3DP process has been used for some time in functional prototyping and design of materials in DoD projects, although not initially for production processes (Freitag, Wohlers, & Philippi, 2003). According to Freitag et al. (2003, p. i), the main purpose of 3DP at the time included “fit/assembly models and prototype parts; creating patterns for prototype tooling and metal castings; and in creating visual aids to support engineering and tool making.” This is substantially similar to product design and development processes today, although as noted above, there is substantially increasing use of direct production of materials. There is also evidence for 3DS in use in military processes. One theoretical discussion posited that 3DS could act as a tool towards knowledge value added in the product lifecycle process for the Fleet Modernization Process (Seaman, 2007). A second report focused on the use of 3D Laser Scanning

Technology (3D LST) as a tool to improving ship maintenance processes (Ford, Housel, & Mun, 2011). These examples, along with other examples of 3DS and 3DP in military use, will be discussed further in the section on product life cycle management.

5. Limitations of 3D Scanning and Printing

There are still some technical challenges and limitations of 3DS and 3DP that need to be considered for their application in some areas. These technical challenges and limitations are important for considering what the applications of these technologies can be one of the challenges of 3DP is the materials specification in use. There are still limited materials that can be used to directly 3D print a given item, although new materials are being developed all the time (and it is always possible to use a lost wax or investment molding technique to cast an item from a different material) (Singh R., 3DP for casting applications: A state of art review and future perspectives, 2010). However, there are also limitations to physical characteristics of existing materials that need to be taken into account, as well as inaccuracies in materials specification that may not yet be detected. For example, a lead alloy solution tested by Singh and Singh (2009) had a recommended minimum shell thickness of 12mm. The authors experimented with the casting process to reduce the shell thickness to 1mm, which reduced production costs by about 45 percent while additionally achieving maximum hardness (Singh & Singh, 2009). A similar study has also shown that decreasing the minimum shell thickness of aluminum casting materials from the recommended 12mm to 5mm resulted in 3.79 percent increase in shell hardness, along with a 54.6 percent reduction in cost and 55.4 percent reduction in production time for casting from this material (Singh & Verma, 2008). Taken together, these two studies suggest that there may be significant improvements available for cost and time by reducing shell thickness. However, this type of testing has not been performed with all materials, and thus there may need to be some experimentation done in order to determine optimal shell thicknesses and other physical characteristics of each material. In some cases, this may not matter as such, especially in rapid prototyping situations where physical measurements and design are the relevant characteristics and physical strength, shell hardness, or other physical characteristics are not as important

since the products will not be used (Dimitrov et al., 2006). Thus, the physical characteristics and properties of the printed material are important, but may be more or less important depending on the situation being studied.

A second limitation is the problem of accuracy, especially dimensional error (Ibrahim et al., 2009). As is the case with Ibrahim et al. (2009), much of the research in this area is focused on the use of 3DP for medical reproduction, since accuracy is a significant concern within this area. The authors tested three processes, including SLS, 3DP, and PolyJet printing mechanisms, on the reproduction of mandibular (lower jaw) anatomy. Such models are commonly used by maxillofacial surgeons as a tool for surgical planning, and as such the dimensional accuracy of the model is critical to ensure accurate treatment of the patient (especially in realignment or reconstruction surgeries) (Ibrahim et al., 2009). The authors found that the dimensional error of SLS was the lowest at 1.79 percent in their test in this area, while the dimensional error of 3DP was the highest at 3.14 percent (Ibrahim et al., 2009). Although they only tested one particular set of equipment for each of these types of technologies, this does suggest that even the most accurate of 3D modeling techniques does have some degree of error. Thus, for any application that requires strict dimensional accuracy from a model, there is a need to determine the error rate of the technology selected, and some technologies may be substantially more error-prone than others.

An informal survey of small and medium enterprise found a number of organizational and technical reasons that there was reluctance to adopt the 3DP process (Park, 2012). Park (2012) discussed the use of 3DP with a number of product designers and others in this sector. The biggest issue identified was cost, with both initial capital outlay and the operational costs of the printers posing a significant barrier to adoption (Park, 2012). Materials limitations, especially the lack of availability of engineering materials (which have higher performance than the standard polymers used in 3DP processes), also pose a barrier (Park, 2012). The accuracy and appearance of the completed project, especially the surface finish, color availability, and structural integrity, reduce the willingness of users to adopt the technology (Park, 2012). These respondents also found some issues with the development of appropriate formats for 3DP, and the

high learning curve associated with modeling 3D objects (especially complex ones) (Park, 2012). Although it seems trivial to use 3DS as a means of producing data files for printing, thus overcoming this problem, this is obviously not a solution for parts that do not have existing forms. Clearly, some of these limitations are more applicable to the naval product development than others. In particular, cost of implementation and the problem of knowledge and tools to produce 3DP files are not as likely to be a problem in a naval product development process as in an SME. However, issues such as availability of engineering materials, accuracy, and surface detail and color are just as likely to pose a problem for naval product designers as for SMEs. Thus, these are significant materials limitations for the use of 3DP for product development.

C. 3D SCANNING AND PRINTING IN CPLM

The final stage of this literature review focuses on the use of 3DS and 3DP in CPLM specifically. The analysis begins with a brief discussion of the product lifecycle management (PLM) process, and then the role of 3DS and 3DP is examined in this environment. The goal of this discussion is to show how 3DS and 3DP techniques have been used previously, or could be used, in key stages of the collaborative product lifecycle, including design collaboration, production and supply chain management, and 3D file management and development.

1. Brief Overview of the CPLM Concept

CPLM is a process that has grown out of the increasingly differentiated needs of firms or other organizations for specific parts and products (Ming, Yan, Lu, & Ma, 2005). According to Ming et al. (2005), CPLM represents a revolution from the previous process, which was focused on mass production. Rather than combining mass-produced products, the CPLM process involves two (or more) organizations working together to produce a product that is specifically suited to the requirements of the customer firm (Ming et al., 2005). The business requirements that this process fulfills include “1) to speed up product development, 2) to enhance manufacturing and supply capability and capacity, and 3) to improve revenue from lifecycle efficiency” (Ming et al., 2005, p. 311). The development of CPLM has been a gradual process of development, with initial

make-to-order relationships (where the customer firm provided specific designs to a job shop) to the current state of design-to-order (where the customer firm works with the vendor firm to meet a specific need, but without a design initially provided) (Ming et al., 2005). Processes included in the CPLM process are "portfolio management, product design, process design, supply, production, launch, service, and recycle" (Ming et al., 2005, p. 311), although any particular CPLM relationship may not include all of these stages. Figure 5 shows a schematic view of the CPLM process and interaction between the firms. As can be seen, processes such as CAD in the design process already enable the integration of 3DS and 3DP processes.

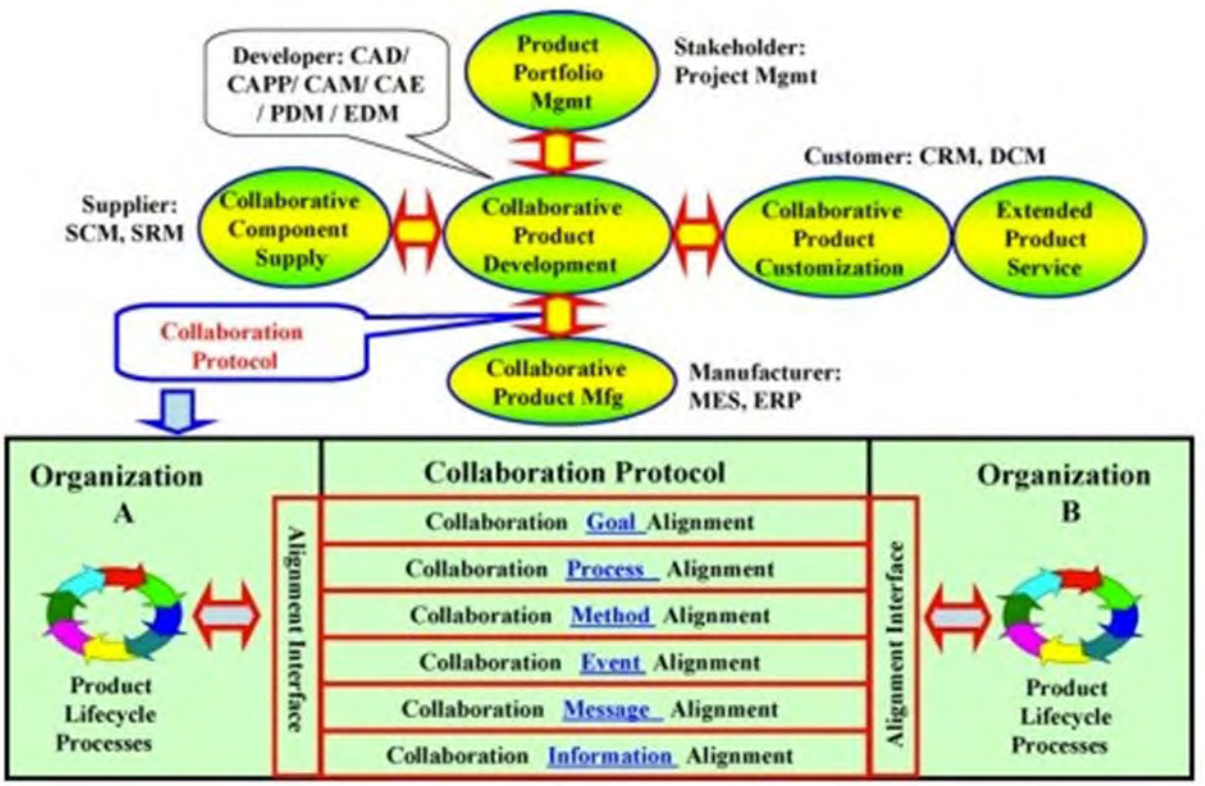

Figure 5. The CPLM process (from Ming, et al, 2008, p. 156)

Typically, the CPLM process is enabled through the use of multiple forms of information technology, as shown in Figure 6 (Ming et al., 2005). These technologies

allow for communication, collaborative design, information and knowledge sharing, and other forms of exchange between the firms as well as dealing with other requirements of the process (Ming et al., 2005).

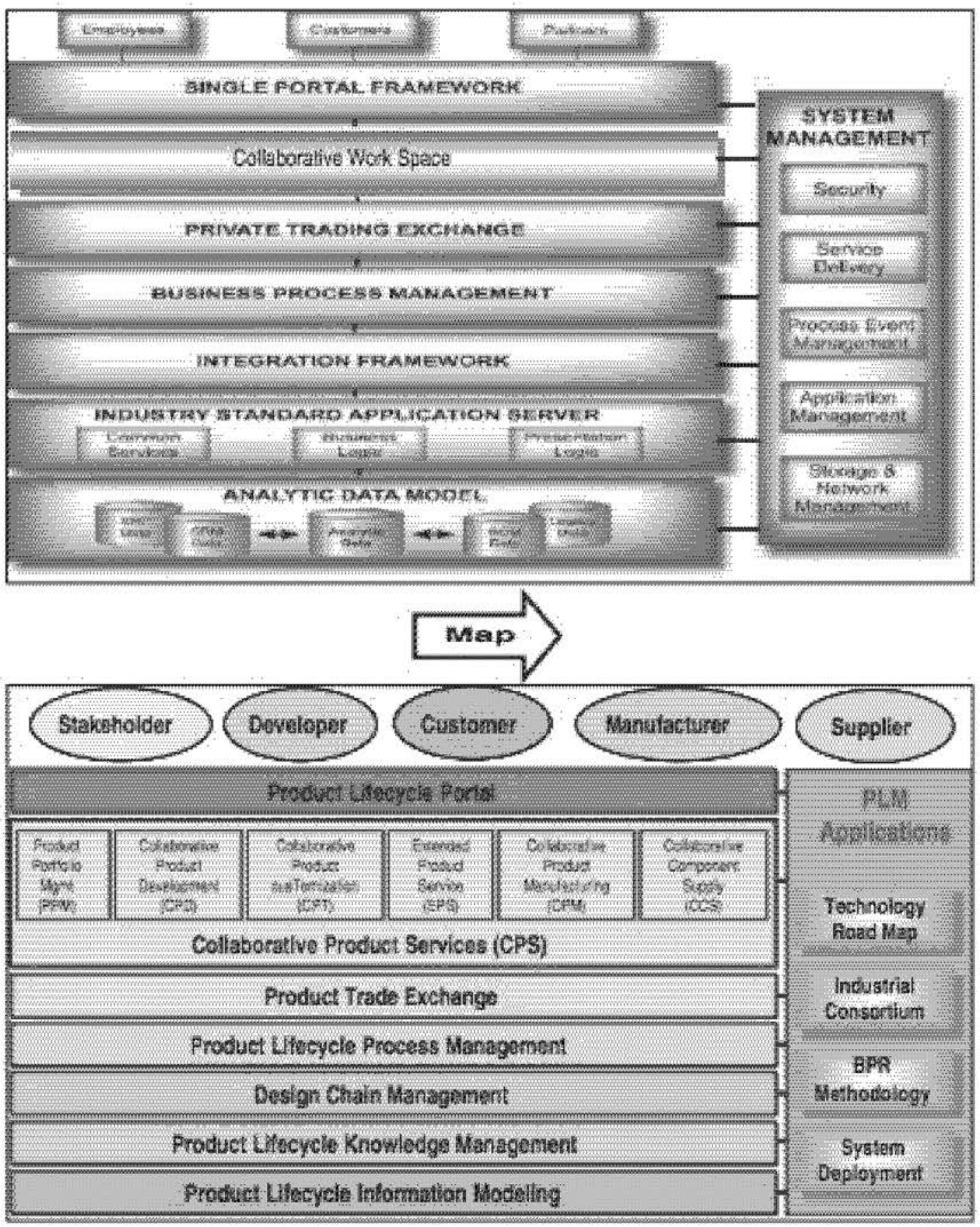

Figure 6. Information technologies and their uses in CPLM (from Ming et al., 2008, p. 316)

Although CPLM was initially based in product design, it has since moved into other areas, such as production planning and manufacturing (Ming et al., 2008). Ming et al. (2008) note that the move to collaborative production planning and manufacturing offers advantages to both vendor and customer firms in a globalized and highly competitive market; it means that customer firms can obtain precisely the parts they require in the required quality, schedule, and other aspects, while vendor firms can produce more products and be assured of markets given their reliable production methods. It also maximizes the value produced along the value chain for the part or component, enabling both vendor and customer firms to gain advantages from the transaction (Ming et al., 2008). However, collaborative production planning and manufacturing does require some specialist information systems, which may or may not be available; in fact, they are often designed by collaborating firms in order to meet their specific requirements (Ming et al., 2008). Ming et al.'s (2008) implementation of collaborative production planning enabled the product designers and managers at both firms to work in a collaborative space that enabled the integration of both firm's requirements, offering the best possible integration for the process.

2. Benefits of CPLM

An industry survey of firms that undertook CPLM showed several advantages and ways in which this process was being used to gain competitive advantage (Aberdeen Group, 2006). This report found collaboration in areas including design, value chain management, project management, real-time meetings, and repurposing of CAD models and 3D publishing practices (Aberdeen Group, 2006). As noted above, 3D technologies are particularly useful in the design and production stages, and thus these areas will be a focus. However, the introduction of 3D publishing and CAD model repurposing offers another possible way that the naval CPLM process could benefit that was not previously discussed in the literature. This should be considered. The findings in regard to design collaboration were particularly important, since use in this stage resulted in better fit between customer needs and attained products, reduced cost, and reduced time required to produce the product (Aberdeen Group, 2006). Furthermore, multiple companies may participate in the collaborative design process; while the general introduction above

conceptualizes the process as only involving two firms, in fact a large number of suppliers and manufacturers may participate in the design process (Aberdeen Group, 2006). This makes the collaborative design process more functional. Value chain collaboration, from sourcing to manufacturing to distribution, is also an important part of the CPLM process (Aberdeen Group, 2006). Value chain collaboration reinforces the benefits of the design collaboration by reducing cost, improving product design and output quality, and reducing time required. Perhaps the most interesting development in this area is the use of CPLM outputs like 3D files to generate manuals and production materials, as well as offer better collaborative views of the product during the design stage (Aberdeen Group, 2006). This benefit is particularly interesting because the 3DP process, in effect, generates an actual 3D object that could be examined or studied, offering the ability to expand the understanding of the object in question and determine how it could be more effectively designed.

3. Using 3D Technologies in the CPLM process

The main question of this research is how 3DS and 3DP technologies could be used in the CPLM process. As noted above, 3D simulations and files are already part of the CPLM process, both in the design stage and in following stages (such as writing technical documentation) (Aberdeen Group, 2006). However, what is in question in this case is how the physical simulation is, or could be, used during the process and what benefits this would offer.

a. Evidence from Naval Studies

This research is based on previous notional studies about the potential for 3DS and CPLM in naval maintenance programs, although no such programs are currently in use. One author has actually examined the potential for using 3DS and CPLM in naval programs (Komoroski, Housel, Hom, & Mun, 2006). Komoroski et al. (2006) studied the specific problem of shipyard planning processes, integrating a number of different techniques and processes and using knowledge value added and real options (KVA/RO) analytical framework. The authors considered 3D LST and CPLM as theoretical additions to the shipyard planning process in order to improve outcomes. The authors used three

different levels of analysis, including existing (as-is), a reasonable theoretical scenario, and an extreme theoretical scenario, in order to determine potential benefits of 3D LST and CPLM (Komoroski et al., 2006). They found that these technologies could potentially provide a number of benefits for the shipyard planning process, including reduced maintenance costs, reduction of DoD labor costs, improving fleet utilization and reducing inventory, and improving current shipyard productivity (Komoroski et al., 2006). There are some limitations to the direct application of this study as applied to the current problem. First, the focus of 3DS was ship-wide (using 3D imagery to capture images of the entire ship and pinpoint trouble spots) (Komoroski et al., 2006), rather than being focused on scanning of single parts, which is the main focus of this research. Second, the authors performed a theoretical proof of concept analysis rather than an empirical analysis, meaning that this research does not provide empirical support for the use of 3DS in the CPLM process (Komoroski et al., 2006). However, despite these weaknesses of the study it is still valuable, both because of its findings and because it shows that the potential or actual use of 3DS is not new in naval shipyard operations and practices.

A second study focused on the use of collaborative techniques and 3D imaging in the ship maintenance and modernization (SHIPMAIN) program (Seaman, 2007). Seaman (2007), like Komoroski et al. (2006), used KVA to examine the potential benefits of 3D imaging during this process. He also used a theoretical proof of concept case to examine the impact of 3D imaging and CPLM on the ship maintenance process, using a hypothetical baseline that was reasonable at the time (Seaman, 2007). This study found potential operating savings of $78 million from the combination of these two techniques (Seaman, 2007). The limitations of application are similar to Komoroski et al. (2006), including that it is a theoretical analysis and that the terrestrial scanning technology is not exactly the same use as is being proposed in this case. However, this study also provides support for the use of CPLM and 3D technologies in naval manufacturing and maintenance practices, especially for the reduction in costs the process could bring.

A third study also supported the use of 3D technologies and CPLM in SHIPMAIN (Ford et al., 2011). Ford et al. (2011) focused on cost savings for the SHIPMAIN program, noting that this represented a significant problem in the DoD generally. They noted that even though the SHIPMAIN program actually had a relatively routine process (including a standard set of repairs and maintenance processes and a relatively standard set of ships on which these should be performed), there had not been a concomitant cost reduction due to learning processes (Ford et al., 2011). Using a similar KVA/RO methodology as used by Komoroski et al. (2006), the authors identified some potential improvements in the SHIPMAIN process that could improve performance. The authors found that the combination of 3D terrestrial laser scanning and CPLM would provide the best benefit in terms of cost savings (Ford et al., 2011). These findings are obviously not revolutionary, as they were also the findings of Komoroski et al. (2006) and Seaman (2007). However, they are quite important because they suggest that the combination of 3D technologies and CPLM was still not integrated into the SHIPMAIN process as late as 2011. Thus, despite ample evidence that these processes should provide significant benefits for SHIPMAIN, there is still a lack of implementation follow-through that will actually realize these benefits.

b. Design, rapid prototyping and CPLM

There is clear evidence that the 3DS and 3DP process should be usable with the CPLM process, particularly during the collaborative design stage (which as noted above is one of the dominant areas of use). Campbell (2006) explicitly acknowledges the need for increased customer input in rapid manufacturing practices, which he envisions as primarily coming during the design stage. He notes that traditional design practices have involved a test of the design in the final stages before production, ensuring that the design is appropriate; however, if this goes wrong the vendor firm can be faced with a considerable cost of rework associated with needing to redo the design (Campbell, 2006). Thus, integrating consumer input into the design stage before its end is required, particularly in rapid manufacturing processes, where there is not a significant amount of time available (Campbell, 2006). Campbell (2006) points to several examples of design failure that were avoidable if customer input were taken into account, making it

clear that this is a valuable aspect of the design process[1]. The use of 3DS and 3DP can help turn the design specification provided by the customer into a rapid prototype, which can be produced using a variety of specific goals (including appearance prototypes, or those that look like the completed product, and functional prototypes, which also work like them) (Campbell, 2006). Unlike conventional prototypes, 3D printed prototypes can be readily handled, relatively is satisfied with the design (Campbell, 2006).[2] 3DS can also be used to produce a prototype by reverse engineering. Furthermore, collaborative 3D CAD processes can be used to co-design a prototype for the product by participants in both firms (Campbell, 2006). Campbell (2006) does not specifically point to the use of these techniques for prototype production in the CPLM environment, but it is clear that the combination of collaborative 3D CAD and the ability to maintain 3D printers on-site means that it would be possible to collaborate during the design process, regardless of whether the naval and other designers were in the same place. This would offer a substantial advantage for the CPLM process. Although Campbell (2006) suggests soliciting customer input through the use of modeling clay, there is no reason that, if provided appropriate tools and knowledge, that the naval designers could not directly engage with the 3D modeling process.

There have been a number of recent developments in CPLM environments that specifically integrate 3D technologies in the design and prototyping process. One recent study focuses on the issue of Web-based collaborative environments and their potential for use with collaborative 3D technologies, which are becoming increasingly common as more firms begin to use CPLM practices (Vezzetti, 2009). This presents a problem because, as Vezzetti (2009) notes, there actually is no Web standard for representation of 3D data. This means that collaborating firms are often using different 3D data formats for collaborative visualization (Vezzetti, 2009). Although Vezzetti

[1] Campbell's (2006) examples focus on the appearance, design, or other elements of the product, and in particular on the gap between product specification and client functional requirements, which could result in a loss of functional capabilities in the completed design. This is particularly important to a naval implementation since many such product designs may be both time-bound and mission-critical.

[2] It should be noted that despite Campbell's (2006) assertion regarding cost, this is only a relative advantage compared to the cost of traditional prototyping, which can require line setup and tooling at a substantial cost. As previously noted by Park (2012), one of the barriers to 3DP implementation is the capital outlay and operational costs of operations, although these are coming down.

(2009) identifies the most useful position for a potential Web-based 3D data format as coming after the design phase, this is not necessarily the case with integration of 3DS and 3DP into a collaborative design process. Instead, during a full-scale CPLM process there would also need to be a shared 3D data format. This is particularly problematic given the diversity and non-standardization of 3DS and 3DP technologies, which may use different types of 3DP formats (Peng & Sanchez, 2011; Reeves et al., 2011). Thus, even though Vezzetti (2009) only discusses a limited area of concern for rapid prototyping and design, this should be expanded.

Although it is not the main focus of this research, 3D technologies can be used to integrate even further into the rapid prototyping process, which may offer even more benefit for the CPLM process. One example is the combination of 3D generated prototypes with an augmented reality (AR) environment, which enables both the physical sharing of the appearance or functional prototype (depending on the choice of technologies and materials) and information about the prototype and its integration into the overall design (Niebling, Griesser, & Woessner, 2008). Figure 7 shows an example of this type of design, with two different potential designs of a Kaplan turbine tagged with AR targets for a head-mounted display. This type of technological augmentation has not been explored in great detail in the literature, but it does represent one way of expanding the CPLM process and offering greater integration of design teams.

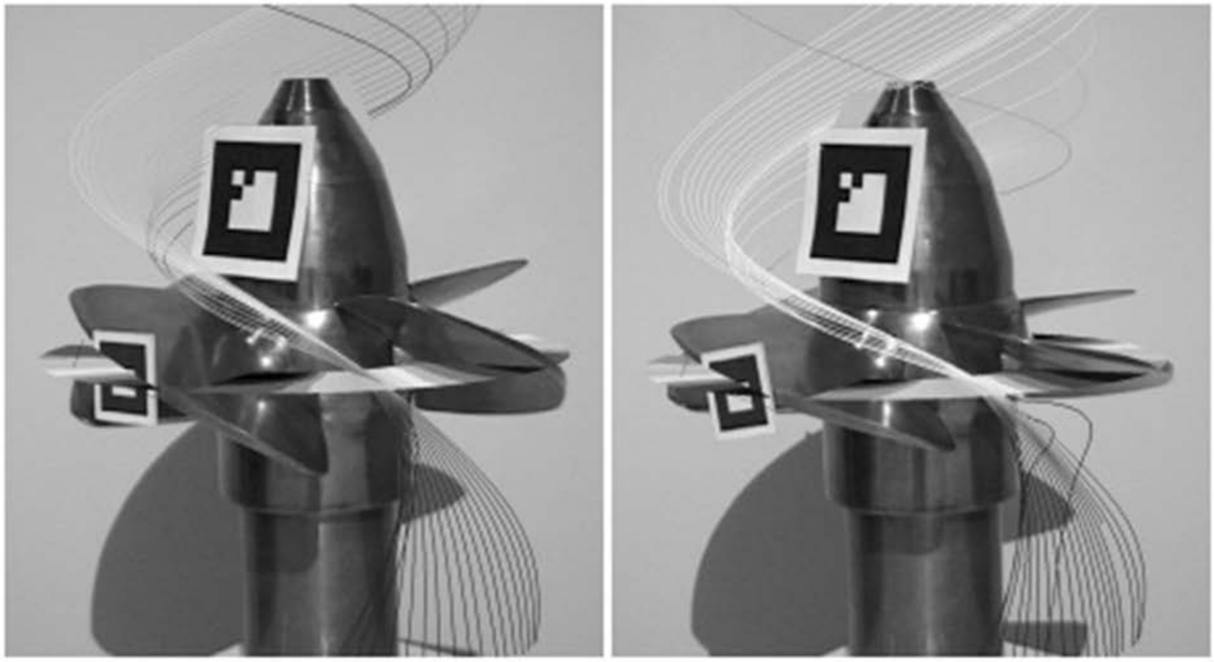

Figure 7. 3D printed and AR-augmented rapid prototypes for a Kaplan turbine engine design (from Niebling et al., 2008, p. 1014)

c. Rapid Production and CPLM

There are no extant academic studies for the use of 3DP-based rapid production methods in CPLM, though Ming et al.'s (2008) discussion of CPLM in production scheduling and manufacturing makes it clear that this is a possibility. One of the few researchers that have mentioned this issue is Vezzetti (2009), who noted the requirement for a standard Web-based 3D data format to be used during the production phase of CPLM. However, he did not explicitly discuss the use of 3D technologies in the CPLM process itself, but rather engaged in a meta- discussion about data representation of the technology's use. The current research will try to fill this gap by researching rapid production and its possibilities in the naval CPLM process.

D. CONCEPTUAL FRAMEWORK

The final task of this research is to identify a conceptual framework that can be used as a means of understanding the research problem and analyzing it effectively. Figure 8 shows the conceptual framework as it is derived from the literature. The

following section provides a summary of how the concepts can be tied together and their backing within the literature. This conceptual framework will be used to discuss the research problem in Chapter IV, as well as providing guidance for development of the methods in Chapter III.

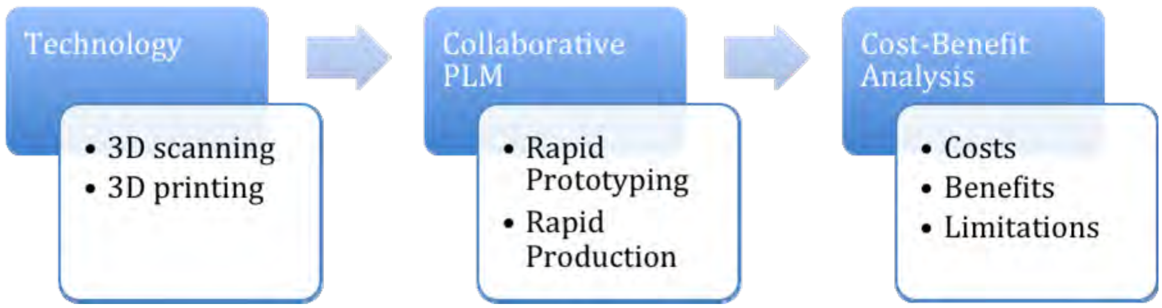

Figure 8. Conceptual framework of the research

1. Technologies

The first element of the conceptual framework is 3D technology, defined as including 3DS of moveable parts and 3DP (including SLS, SLA, and any other technique that is considered to be appropriate by designers). 3DS can generally be described as the process of imaging an object and then creating a 3D digital mesh that can be manipulated and changed (Vaughan, 2012). 3DS may be used for a number of purposes, including design and development, fitting of products (such as in anthropometric measurement), and reverse engineering (Paquette, 1996; Peng & Sanchez, 2011; Vaughan, 2012).

3DP can be thought of as the other side of 3DS, although its inputs do not need to come from a 3D scan. 3DP involves the transformation of a 3D data file or simulation to a physical file using additive deposition of materials (such as polymers, metals, composites, or other materials) (Evans, 2012). There are a wide range of 3DP technologies, which tend to use extrusion, granular deposition, or light polymerization as a means of depositing and forming the materials (Evans, 2012). 3DP is used in a number of different ways, including rapid prototyping and rapid production (either as a means of producing a mold for lost-wax or investment casting or as a direct manufacturing method) (Bak, 2003; Budzik, 2010; Chua et al., 2010; Jacobs, 1992; Vaezi et al., 2012).

2. Process

In the conceptual framework, 3D technologies are applied to the CPLM process, especially at the design and production stages. CPLM involves the development and production of products between vendor and customer firms (and sometimes including multiple firms) (Ming et al., 2005; Ming et al., 2008). However, there has been relatively little research into CPLM and the use of 3D technologies. Application at the design stage is well supported within the literature, especially in terms of support for naval product management concerns (Campbell, 2006; Komoroski et al., 2006; Seaman, 2007; Ford et al., 2011), while application at the production stage is more limited, with only one author touching on the potential use of 3D technologies in CPLM (Vezzetti, 2009). Thus, one task of this research will be describing how 3D technologies can be used in the productive stage of CPLM.

3. Costs, Benefits, and Limitations

The final aspect of the conceptual framework is the costs, benefits, and limitations of the 3D technology technique. The operating costs of both 3DS and 3DP have been coming down in recent years due to advances in technology and development of new forms (Evans, 2012; Peng & Sanchez, 2011). However, cost still represents a significant issue for the users of this technology (Park, 2012). The specific costs of the technology are not quantified by the literature, but could include operating costs of the 3DP process (noted by Park (2012) to be exceptionally high) and the costs associated with CPLM itself, which can also be high given the frequent need to design or modify collaboration systems (Ming et al., 2005; Ming et al., 2008). 3DS can be an inexpensive process, with COTS scanners performing as well as expensive photogrammetry machines for some applications (Aguilar et al., 2009). However, there are still costs associated. Thus, there are some notable costs associated with the use of 3D technologies in the CPLM process, which will be explored in this research.

The benefits of the CPLM process itself are known to include reduced costs, reduced time to shipment, and improved reliability of designs in terms of what the customer desires (Ming et al., 2005; Ming et al., 2008). This offers benefits to both the

customer firm and the vendor firm, due to reduced costs associated with the project. The benefits of the 3D prototyping process are mostly focused on the ability to provide customers with the ability to examine and inspect their product designs prior to finalization, reducing the associated cost (Campbell, 2006). For rapid production, 3D technologies offer the opportunity to immediately produce a given part from a stored design, reducing issues with the supply chain.

Each of these technologies has its own limitations, though the extent to which these limitations is applicable may vary depending on the specific scanning or printing technology selected. Some of the limitations of 3DS include accuracy (especially dimensional accuracy and geometric distortion) and representation of surface detail, though resolution is not a limitation and most modern scanners are suitable for product design (Park, 2012; Peng & Sanchez, 2011; Zalama et al. 2011). Some of the limitations of 3DP include lack of functional characteristics of the materials (such as strength, stiffness, heat resistance, and so on), lack of surface detail and color and lack of geometric accuracy (Bourell, 2006; Park, 2012). Identifying further limitations is not the main task of this research, but it will be kept in mind when considering the suitability of the process.

E. SUMMARY

This chapter has discussed and analyzed the processes of 3DS and 3DP and their application in design, prototyping, and manufacturing processes similar to naval shipbuilding. The first task that was undertaken was to provide a high-level explanation of the 3DS and 3DP processes as they would be explored in this research. This description was intended to show how the processes are integrated into the product design process, rather than provided a detailed technical analysis (which is outside the scope of this research). The second task of the chapter was to engage with the empirical literature on the topic of 3DS and 3DP, especially in terms of its use in the design and manufacturing process. This task was undertaken to show that the processes are used in multiple other design contexts. It was also focused on identifying the costs and benefits of the 3DS and 3DP processes. While 3DS is primarily useful for reverse engineering

and rapid production (in some cases), 3DP is more flexible. There is a variety of types of material that can be used for 3DP, such as metals, polymers, or starches. There is also a variety of 3DP processes (most generally termed additive production), which offer different levels of accuracy and detail. These processes can be used for a variety of different purposes, including design (such as rapid prototyping), mold-based production of small lot items, and even production of replacement parts. There are costs and limitations to the 3DS and 3DP process that need to be considered, including materials limitations and accuracy. However, despite these limitations, there are many different applications that can be found for the process. Ultimately, this literature review shows that 3DS and 3DP are established parts of the design and production stages of the product lifecycle in other organizations. This finding offers support for their integration into the naval product lifecycle process. In the next chapter, the conceptual framework built within this chapter will be used to outline an analysis technique for cost/benefit analysis of 3DS and 3DP in the naval product lifecycle.

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III. METHODS

This chapter introduces the methodology used to arrive at the findings of the main study, which are presented in the following chapter. In order to define the methodology, the researcher took into account methodologies that had been used by previous researchers in order to examine similar problems. Studies by Seaman (2007) and Komoroski et al. (2006), as well as information from Park (2012), have been used to construct the methodology. The method used is a multiple case study based on three hypothetical scenarios, including design and development use, small- scale production (replacement parts), and full-scale rapid production. In this chapter, the methods used are outlined, beginning with a discussion of the research philosophy and moving to the analytical framework, methods of data collection and analysis, and limitations of the study method.

A. RESEARCH PHILOSOPHY

The research philosophy this research is based on is the pragmatic philosophy. Pragmatism, which was established mostly by American philosophers such as John Dewey, Charles Peirce, and Richard Rorty, holds in short that the method used to arrive at a particular conclusion is not as important as the conclusion itself (Hookway, 2008). This is encapsulated in the pragmatic maxim, which can be encapsulated as the idea that the consequences of a given action are the most important aspect of the action itself (Hookway, 2008). Following this research maxim, the most important question for the researcher is not the strict rigor of the research method, but instead: did it work? This is a highly useful approach for a number of research areas, including business and teaching, that focus on results and where research is routinely conducted in situ (Creswell, 2009). In this research, a purely theoretical approach is chosen, but the notion of the pragmatic maxim is still the most important aspect of the outcomes and focus of the research. In other words, this research is based on identifying practical changes that will work in the research setting; however, those practical changes will be applied.

B. ANALYTICAL FRAMEWORK

This research uses a two-stage analytical framework, modeled on Seaman's (2007) theoretical exploration of using 3DS for the modernization program. In the first stage, appropriate 3DS and 3DP installations for three levels of use will be identified, while in the second stage the costs and benefits of these technologies (including capital, human resources, and other costs and benefits) will be explored. Figure 9 shows the basic analytical framework that is used, along with the methods used for the process.

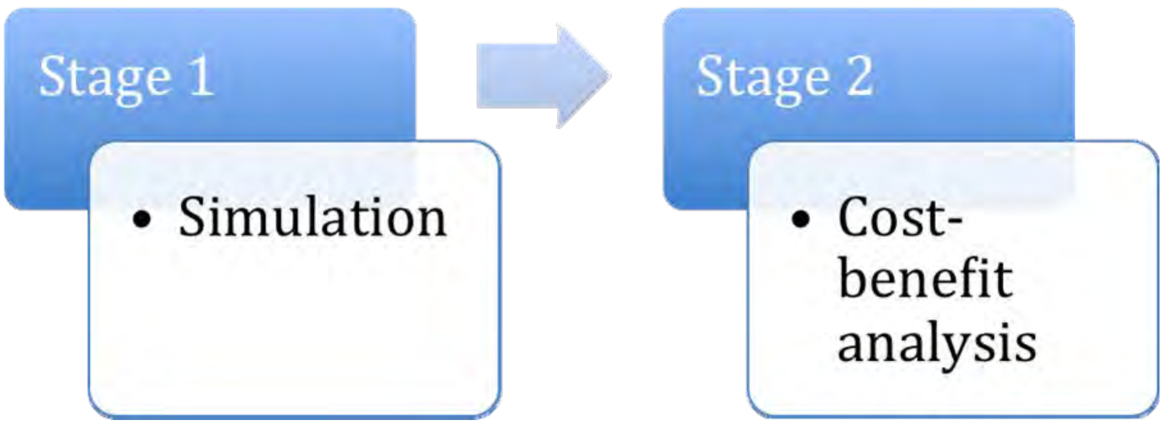

Figure 9. Analytical framework for the analysis

1. Simulation

The first stage of the process will be a simulated process of requirements determination for naval installations of varying sizes for the CPLM process. These simulations will include:

- Small: a small installation intended primarily for collaborative product design and development, including reverse-engineering and production of prototype parts. This installation will be localized, including one product design firm and one naval product design unit.
- Medium: a medium-sized, distributed installation intended for small-scale production (such as production of hard-to-find replacement parts) in locales such as regional distribution centers or onboard ship.
- Large: a large centralized distribution installation intended for full rapid production of parts.

The simulations are based on previous research (detailed in the literature review), which describe the equipment availability and requirements for installations of this size and purpose, especially Seaman (2007) and Komoroski et al. (2006). This is supplemented by information about current CPLM processes and product reviews and trade information about specific, current models of 3D printer and scanner. For each simulation, the following information will be determined:

- The number of 3D printers and scanners required and appropriate choices of equipment (1-3 options) for each type of technology
- Additional physical infrastructure required (Internet linkage, other technologies, etc.)
- Human capital required (skills and additional training)

Operating costs are not included in the simulation, because they are highly variable and dependent on usage scenarios, materials, and approaches used. These costs are expected to be relatively small compared to the capital outlay for equipment and physical plant. Furthermore, they are use-dependent but will not otherwise vary depending on the size of installation. Thus, these costs can be assumed to be relatively low and consistent between simulation scenarios.

2. Cost-Benefit Analysis

Following the formulation of theoretical scenarios for the installations listed above, the second stage of analysis will be CBA. This was an approach used by Seaman (2007), Park (2012) and others in previous explorations of 3D technologies and their use in product design and production areas. CBA can be defined as a decision-making and analysis approach that comprehensively identifies the costs (including financial and non-financial costs) and benefits (including financial and non-financial benefits) of a proposed process, project, or approach, and then compares these costs and benefits to determine whether the process or project is worth implementing from a business perspective (Mishan & Quah, 2007). CBA can be used across a variety of different scales and at different levels of formality in order to make decisions, from the national level to the level of a small business (Mishan & Quah, 2007). Typically, a CBA process may rely on quantitative data (where available) and qualitative data (Mishan & Quah,

2007). It may be implemented using primary research (such as feasibility studies or existing installations), simulation or secondary research (Mishan & Quah, 2007). In this analysis, the approach of simulation has been chosen due to a lack of existing information available and lack of resources to conduct feasibility studies.

There are several key aspects of CBA that need to be taken into account. First, the balance of costs and benefits in terms of financial benefits is typically described in terms of their Net Present Value (NPV), a standard accounting measure meant to represent the sum value of future cash flows in current dollars (Brent, 2006). However, the qualitative aspects of the decision are not as simple to standardize; for example, stakeholder benefits and costs need to be taken into account, but these can rarely be reduced to a quantitative figure, especially without previous experience of impacts (Brent, 2006). For both qualitative and quantitative analyses, there needs to be some accounting for uncertainty, given that both of these areas are likely to be imperfectly projected (Brent, 2006; Mishan & Quah, 2007). In the quantitative analysis, this can be represented by a sensitivity analysis, which performs the analysis based on various levels of cost and return in order to determine where the project will need to fall in order to have positive returns (Mishan & Quah, 2007). A limited risk analysis will be performed in the qualitative analysis, based on the available public information about the implementation scenarios. Non-monetary costs will be examined as well in the qualitative analysis, including cost of organizational change, manpower issues, and other aspects of non-monetary cost and benefit.

C. RESEARCH METHODS

Using the methodological framework above, a method of data collection and analysis has been constructed that will allow this research to be robust despite its reliance on secondary data.

1. Data Collection

Data collection will be based on secondary data sources and trade sources. The first aspect of the data collection will be identification of requirements from the case studies and other studies profiled in the literature review. This will provide approximate

requirements for each of the three simulation scenarios that will be used. Information will then be collected from published government materials as well as trade sources about the potential costs, such as human resources costs and equipment costs. This data will be arranged in two datasets, including a quantitative dataset in Excel (detailing the financial cost of equipment for each scenario) and a qualitative dataset (detailing stakeholders, risks, and other non-financial information).

2. Data Analysis

The data analysis will take part in two stages, as detailed above. This will include:

- Detailing scenarios, including sensitivity scenarios for each of the three installation simulations.
- Performing quantitative CBA based on financial costs and benefits.
- Performing qualitative CBA for risks and benefits not directly related to financials.
- Comparing results across models in order to identify the best-choice scenarios and drawing conclusions about the viability and utility of each of the scenarios individually.

The goal will be to 1) identify the potential a) benefits, b) costs, and c) limitations as it would apply to the product lifecycle development process in the Navy. The final stage will be to identify a plausible testing method for determining whether this is appropriate, including methods, hardware, and training requirements). This testing method will be recommended in the final findings of the research prior to implementation.

D. LIMITATIONS OF THE RESEARCH METHOD

Although the researcher has attempted to make the research method as robust as possible, there are still some limitations that are inherent in the method.

1. Credibility of the Study

Although some quantitative methods are used in this study, the research method is primarily qualitative, and as such dependent on the judgment of the researcher rather than randomization of the sample. This means that the credibility of the study (such as its

reliability or validity) is dependent on the credibility of the researcher, which must be demonstrated based on qualifications and previous experience as well as knowledge of the topic (Creswell, 2009). The literature review shows that the researcher has conducted a comprehensive survey of the literature and identified the current issues and gaps that this research must address. Additionally, the researcher has undergone training in the specific issues inherent in this research as well as more general aspects of the research process, such as research methods and statistics. As such, the researcher believes there should be few issues with the credibility of the study.

2. Methodological Limitations

This research is fundamentally a case study based on simulated situations and data. Because of this, some of the methodological limitations that apply to case studies also apply here, such as the selection of data by the researcher (which can introduce bias) and the inapplicability of case study findings directly to other situations (Yin, 2008). The researcher does not view these limitations as a reason not to use this method, but it is something to be aware of and which has been taken into account.

3. Data Limitations

Most of the case studies available have not focused specifically on military applications of 3D technology, although a few have. Additionally, primary data from existing programs is not available in detail. As such, although the researcher has attempted to make the best possible estimates, this continues to be a limitation in the research method.

The data will also be limited in that they will be time-dependent. Because the technology of 3DS and 3DP has changed rapidly over the past decade, as well as the accuracy and reliability of these technologies, previous feasibility studies conducted in the mid-2000s may need to be updated already in order to account for these changes. It is not expected that this study will have any greater longevity, and it is expected that the findings of this research would need to be updated (at least in terms of the cost and specification particulars of the scenarios) within three to five years.

E. SUMMARY

This chapter has discussed the methods used in this research in order to provide a realistic (though simulated) CBA of using 3DS and 3DP within the naval CPLM process. The research is based on a pragmatic philosophy, holding that the outcomes of the research are more important than the precise methods by which these outcomes were arrived at. Using this philosophy, the research is structured as a two-stage, qualitative-led inquiry, in which first scenarios for three installations of varying sizes, and for various purposes, are defined. Following this definition, which includes specifics about the type of 3D technologies required as well as other information needed to implement a 3DS and 3DP program at certain scales, the CBA framework is used to understand the relative costs and benefits of these installations. This includes quantitative analysis of financial costs and benefits, sensitivity analysis, and stakeholder and risk analysis, which are conducted using qualitative research. In the next chapter, the findings of the research are presented, showing how the scenarios were formulated and the outcomes of the CBA.

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IV. FINDINGS AND DISCUSSION

The methods chapter above outlined an approach to understanding the problems and benefits of implementation of 3DS and 3DP technologies in the CPLM process used in the Navy. This was built on the literature review chapter, which both outlined specific costs and benefits that might be found for this implementation and offered insights into the technology itself. In this chapter, the findings of the two-stage analytical process are presented. The three scenarios are each first described in detail, to show what the problem is and what type of installation will be used to solve it. A detailed scenario for the specific capital and human resources investment required for implementation then follow. Finally, a CBA based on this detailed scenario is offered for each installation type. After the construction and analysis of each of the three theoretical scenarios, a discussion is held that compares and contrasts each of these scenarios and examines how the findings show each of these scenarios to be of benefit. This section also integrates information from the literature review (Chapter II) to provide critical insight into the discussion area.

A. ASSETS

Based on existing practices for tool acquisition, the financial cost estimates for the models below are based on a set of standardized 3D printers and scanners. Table 1 summarizes this equipment. Printer costs are based on estimates provided by sales staff (NextEngine, 2013).

Application	Equipment	Cost
Scanning	NextEngine portable 3D scanner	$2,995 (NextEngine, 2013)
Design Printing	3D Systems Projet 3000 3D printer	$29,995 (Est.)
Production Printing	iPro 9000 SLA Production 3D printer	$45,995 (Est)

Table 1. Equipment used in 3DS and 3DP scenarios

In terms of technology, SLA has been selected based on the existing state of the art and the common use of SLA to print composite and polymer materials. This does not provide composite printing without modification, which needs to be taken into account on the shipboard program.

Personnel costs are based only on provisioning and training, and do not include day-to-day operational costs. Obviously, a fully employed technician will offer more benefit than apartially employed technician. However, for Scenario 1 and 2 (product design and shipboard machine shop work), 3DS and 3DP are presumed to be an addition to a range of work duties for personnel, rather than full-time activities, and it is difficult to predict what percentage of a given technician's time may be devoted to 3DS and 3DP. Thus, per-hour work costs are not included in the financial measures.

B. SCENARIO 1: PRODUCT DESIGN AND PROTOTYPING

The first scenario that is discussed in this research is the most basic use of 3DS and 3DP, its use in the product design cycle. This is the smallest scenario in scale and cost, and it is also the most basic scenario because it is generative of the two manufacturing scenarios. Specifically, the use of 3DS and 3DP during the product design stage would be required in order to create shapefiles or other 3D records for the production process. As such, this is the foundational scenario and the one that needs to be addressed first.

1. The Usage Scenario

The usage scenario that is detailed in this case is the use of 3DS and 3DP technologies for product design and development. The main purpose of 3DS and 3DP in this scenario is to facilitate the rapid exchange of prototypes, enable changes in design, and allow Vendor and

Navy designers to work together more closely to generate designs. In this scenario, teams of product designers working at the vendor company and on the Navy's product design teams use 3DS and 3DP technologies to exchange ideas about the products being designed. For example, 3DS may be used to reverse-engineer an existing

part that will be reused in the new design, paying particular attention to scale accuracy and avoiding stretching. 3DP is then used to print visual prototypes (or prototypes that are used to illustrate the appearance of parts and see how they fit together). This printing can take place at any location in the Vendor or Navy installations, since the 3D CAD files used to generate the printing are easily exchanged. The ability to produce functional prototypes is somewhat limited because of the lack of availability of materials, though products created from some metals, polymers, and composites can be constructed. Multi-material prototypes can also be constructed using functionally graded printing. Although this is highly important work, it requires a relatively low investment in capital equipment, since workgroups are small and can be expected to share equipment.

2. Financial Costs

This scenario is based on a single team of 4-10 Navy product designers working with a team of the same size in one to two suppliers. The estimated requirements for a team of this size include:

- One 3D scanner per installation
- Two design printers per installation

No additional personnel are required for this installation, but it should be assumed that designers and other team members would need to be trained on how to use the equipment and 3D methodologies. The assumed training requirements are 40 hours training (including procedural and methodological training) per member of staff assigned. Table 2 shows the estimated cost of financial cost of implementation for the design scenario. These figures reflect the cost per team, and assume that suppliers will equip and train their own staff members. Assumed training costs are $30/hour per team member. These training costs assume that the size of the team will be appropriate to the level of activity demanded from the team, and the manpower assigned will not be under-utilized. If this is not the case, the financial benefit will be reduced (unless the members of the team can be partly assigned to other tasks).

It is assumed that no additional hardware or software will be required other than that procured through normal methods or provided with the scanners. This shows that the

cost of implementation is not necessarily that high, especially given the flexible cost of the printers (which are fixed on teams between four and 10 members, and given experience may be higher than estimated). It should also be noted that these are start-up costs only, and could be expected to become lower over time since substantial retraining of the entire team would not be required and the equipment would last for some time. However, it also does not take into account consumables, which do pose a significant part of the cost of the 3DP process.

	Estimated Costs		
	4-man team	6-man team	10-man team
Equipment			
Scanner	2,995	2,995	2,995
Printers	59,990	59,990	59,990
Personnel Costs			
Training	4,800	7,200	12,000
Total Costs	67,785	70,185	74,985

Table 2. Estimated financial cost of implementation for design team implementation of 3DS and 3DP

3. Non-financial Costs and Benefits

An important aspect of the costs and benefits associated with the scenario is the non- financial costs and benefits associated with the training period. These non-financial costs and benefits include improvements to efficiency and other gains, as well as costs in terms of supply and other issues. Some of the costs and benefits are summarized here. However, this is not an exhaustive list, and some are dependent on actual implementation. Thus, these costs and benefits should be reassessed in light of implementation plans.

One of the most significant benefits for design is the ability to rapidly trade prototypes between the design teams in the Navy and suppliers, which can be geographically far apart. Rapid prototyping enables teams located in different areas to pass 3D files that can be printed using a 3D printer (Chua et al., 2010). The rapid prototyping process is particularly useful for the product development process because it allows for the development of functional prototypes that can be handled, fit together, and

assessed for surface design and to some extent functionality. SLA, the process used by the 3D printers selected for this analysis, is particularly useful because it provides a high degree of fidelity in dimensions, surface detail, and other aspects of the design with a minimum amount of skewing (Melchels et al., 2010). This allows the SLA process to effectively print even very small items, including ceramic superconductors in unique shapes (Nan et al., 2011). Thus, there would be considerable flexibility added to the design stage as designers could rapidly pass designs between teams, produce design and some limited functional prototypes, and speed up the product development process. This would significantly reduce the time period and increase the efficiency of the design process for the naval developers.

While there are some clear benefits to the design process, there are some limitations as well. SLA cannot be used directly in industrial applications because of the tendency to create surface cracks and have some loss of fidelity (Li et al., 2011). While this is not a problem for design prototypes, it could be problematic when assessing the appropriateness of functional prototypes for designs. There are also issues with materials strength and physical properties of some materials that make the use of 3DP as a functional prototyping method difficult (Bak, 2003). This means that in order to create functional prototypes, or those prototypes that are assessed for fit and functionality rather than simply for surface design, there would need to be more traditional methods of prototyping used. Thus, there would need to be some development of functional prototyping methods that did not require the use of 3DP to allow for these issues to be met.

There are some clear advantages for the Navy's collaborative product development lifecycle. In particular, it would allow for development of new parts and assemblages between geographically separated design teams, taking into account different technologies. It would also speed up product development, which could reduce the supply chain development time in general. However, this effort would be primarily be directed toward new product development, and not focused on meeting existing supply chain demands for products that have already been developed. It also would not address product availability or supply issues, particularly for obsolete or rare parts that might be

required. Thus, this is a useful scenario, but it does not provide a complete supply chain solution. Additional tools, and potentially additional uses of 3D technologies, would be needed in order to fully meet all the requirements of the CPLM cycle. It may be possible to maximize efficiency of investment in hardware. It should be noted that there are less expensive 3D printers, which could be explored for use in larger teams. There is also the possibility that 3D printers could be used across multiple teams, which would depend on workflow requirements. These issues would need to be managed at the project level, since it would also depend on the extensiveness of use. However, this does suggest that at the product design level, there would be significant benefits that would outweigh the costs associated with the project.

C. SCENARIO 2: DISTRIBUTED, SMALL-SCALE PRODUCTION

The second scenario is also based on the literature review. It is intended to resolve a particular supply chain problem of getting parts to remote areas, especially parts that are infrequently used or may have an uncertain supply. This is somewhat larger in scale than the previous scenario. While it depends on the previous scenario to some extent to provide the 3D CAD files for new parts, there is no reason (barring legal complications) why older parts cannot be scanned using 3DS equipment and then distributed as 3D CAD files.

1. The Usage Scenario

In this scenario, 3DS and 3DP is used in a distributed fashion to improve ship maintenance and facilities maintenance by reducing supply chain issues. 3DS is used from a central location to build a library of 3D CAD files for various parts, especially parts that are difficult to replace for some reason. While there should be a prioritized list of parts to process through this facility, it could also take requests for scanning parts required. The other half of this operation is at remote locations (such as onboard ships or at land-based facilities), where 3D printers and lost-wax casting facilities would be installed in the maintenance department. These facilities would allow maintenance engineers to print parts made of polymer, composite, or some metals, while polymer forms could be used to cast parts if they cannot be printed due to materials requirements.

This would allow for replacement of parts that are not available for some reason, such as general part scarcity or simply if they are not stocked at that location. The use of 3DS and 3DP in this way could make maintenance and repair activities much less complex, and reduce the amount of downtime spent waiting for replacement parts. However, it also requires substantial investment in equipment for the centralized parts digitization library as well as the remote printing and casting locations, and training for personnel in both of these areas.

2. Financial Costs

This scenario relies on two areas of finance, including a central 3D library (including staff members and storage) and shipboard maintenance outfitting (including training and equipment). Because of the limitations of lower-quality SLA printers, this scenario would require a production-level SLA printer, increasing the cost of production. Some of the costs were impossible to estimate, including the cost of lost-wax or investment casting equipment on board ship. Thus, this scenario is only applicable to materials that can be printed using a 3D printer, which as previously discussed include primarily polymers, metals, and a limited range of composites. The estimate includes three levels of outfitting, including per ship as well as outfitting all aircraft carriers (11 in total) and every ship in the naval fleet (currently holding at

298 ships based on 2013 plans (Cavas, 2012)). It also includes an estimated rate for a 10-TB data library and four technicians for full-time scanning of fleet parts, which would be used to provide plans for parts. It includes only training cost for library technicians and it is also assumed that shipboard maintenance technicians will require 200 hours of training (five times as much as designers), because they do not necessarily have pre-existing familiarity with 3D design techniques required. This scenario assumes that team members will perform the 3D tasks along with their regular duties, rather than operating at full capacity as in the scenario above. Thus, the benefit of training will be lower. This analysis shows that the per-ship cost of this program is relatively high, and

the implementation of the program on the whole would be substantially more expensive than the design team implementation above. Table 3 summarizes the costs associated with these plans.

	Estimated Costs Per Ship ($)
Shipboard Equipment and Personnel	
Scanner	2,995
Printer	45,995
Training	12,000
Cost per ship	60,990
3D Library Costs	
Scanners (12)	35,940
Printer	45,995
Data storage and servers	5,000,000
Technicians (4 technicians at 80 hours training)	9,600
Total Library Costs	5,091,535
Total Costs	
One ship	149,530
Aircraft carriers only	787,475
Full fleet	22,374,045

Table 3. Estimated financial cost of implementation for shipboard maintenance implementation of 3DS and 3DP

3. Non-financial Costs and Benefits

As with the previous scenario, the consideration of the non-financial costs and benefits of the shipboard maintenance plan must be considered. This is particularly important given the much higher cost associated with the development of the program compared to the design maintenance team (and as we will see currently, also with the centralized parts production facility team). The exceptionally high per-ship cost of outfitting is required by the need for production-level SLA materials, which means that the program would have a higher cost per installation than the design scenario.

The main benefit of having 3D technologies onboard ships is that it will ease supply chain control issues, particularly those associated with rare or obsolete parts or

those that are simply not in stock. It would represent a form of rapid production, which is facilitated by 3D technologies (Ming, 2008). The use of rapid production has a number of benefits, including a small batch size, rapid tooling, and relatively low costs according to other job printing processes (Ming, 2008). It would also make it much easier for shipboard maintenance engineers to control their inventory requirements and costs. The ability to store 3D specification files in CAD, rather than physical parts, is a significant benefit to complex supply chain management problems (Campbell, 2006). Furthermore, it would allow for the reduction of parts inventory carried on ship, which could improve efficiency and fleet utilization (Komoroski et al., 2006). Because of this, there are some reasons to consider the use of shipboard production of parts, even though the cost is relatively high.

Many of the same issues that plagued the design scenario would also be substantial issues for the shipboard maintenance scenario. For example, issues with surface pitting, materials strength, and the physical properties of materials would still be an issue (Bak, 2003; Li et al., 2011). In fact, these issues would be even more problematic in the shipboard scenario, since these parts would actually be intended for production and would need to have full material strength of the original parts in order to be effective substitutes. This is a serious disadvantage. It is a problem that can be overcome using lost-wax or investment casting, in which the printed object produced by the 3D printer is used to create a mold, into which appropriate materials are cast (Evans, 2012). However, lost-wax casting requires space, time, and materials that may not be available aboard ship easily, as well as posing a potential worker safety problem. This suggests that there may be a serious problem involved in the development of a program intended for production of parts other than polymers or a small number of metals. Furthermore, although some parts may be printable using this approach or using functionally graded printing (to produce composites or mixed-material designs), there is still the problem of the cost of substrates or printing materials, which could substantially reduce the cost savings associated with reducing inventory. Overall, these limitations are substantial and could reduce the benefits offered from having immediate access to parts.

Overall, the shipboard maintenance program would serve a useful purpose of reducing supply chain issues and allowing maintenance engineers to easily reproduce failed parts, particularly those that are rare, obsolete or otherwise difficult to find. However, the cost of implementation is high, and may actually be even higher than is estimated here due to the need to train engineers who are likely to require substantially more training than designers. This makes the implementation of shipboard maintenance programs more costly and more complicated than the design program. It may be of limited use across some ships, such as aircraft carriers, where there may be a larger need for supply chain flexibility as well as a greater demand for polymer and composite parts. Overall, however, the use of distributed 3D technologies in shipboard maintenance for production of the occasional missing part seems to still be economically inefficient and difficult to plan for. This should not be a recommended approach in most cases. However, it could have a useful limited application in situations where there are long periods without contact with the rest of the fleet or where there is a growing demand for difficult to find parts. However, it is inappropriate as a general approach.

D. SCENARIO 3: CENTRALIZED, LARGE-SCALE RAPID PRODUCTION

The final scenario is the most extensive scenario offered. It is focused on large-scale rapid production, using either 3D printers themselves as the production machinery or using 3D printed forms to generate molds for lost-wax or investment casting, depending on the finished product material and physical requirements. This scenario is in some respects built on the previous two, since to be most effective it would require 3D CAD files from the product design process or generated after production using the same 3D CAD library construction as in the small-scale, decentralized production scenario. However, the use of rapid production has several potential benefits, including that it could reduce tooling time and bring products into the supply chain faster, which means that it should be considered despite the much greater expense.

1. The Usage Scenario

This scenario involves a centralized production facility devoted to the production of parts using the 3D CAD files produced as final products by design teams, or generated

from existing parts through a 3D CAD library. The production facility could produce some parts, especially those made from polymers or composites, directly using 3DP machines. However, it could also use lost-wax casting based on 3D forms to produce forms from other materials, such as metals, ceramics, concrete, or even glass. This type of production would take longer, but would increase the flexibility of the production facility substantially. The production facility would use rapid production methods as detailed above in order to schedule the various parts required, with small batches being run around larger batches. This would require a substantial investment in various types of production equipment as well as the 3DP machines. It would also require training production facility personnel in the use of the 3DP machines and the new machinery required for casting various materials. The large-scale production scenario is also dependent on the establishment of 3D CAD in the product design process, and if it is to be used with older parts also on the establishment of a 3D CAD library.

2. Financial Costs

The financial costs associated with this scenario are a balance of the previous two scenarios. While the same costs would be associated with the data library and technicians, the actual production would be integrated into the data library setup and no training of shipboard technicians would be required. The rates for the data library and casting machinery are estimated based on best-guess figures, since no firm figures were available. It is assumed that four technicians would staff the library and manage the production equipment. Distribution costs would be subsumed in existing supply chain processes, as parts would be dispatched using standard supply chain avenues. This suggests a mid-range cost for the production facilities in this case. Table 4 summarizes the costs associated with this project and the required personnel. It is assumed in this case that the library and production technicians will be fully utilized; if they are not, then the financial benefits will fall.

3D Library and Production Costs	
Scanners (12)	35,940
Printer	229,975
Technicians (4 technicians at 80 hours training)	9,600
Total Library Costs	275,515
Production setup (CNC and Lost Wax)	2,000,000
Total costs	2,551,030

Table 4. Estimated financial cost of implementation for centralized production facility implementation of 3DS and 3DP

E. COSTS AND BENEFITS

As with the previous two scenarios, it is once again appropriate to consider what needs this would fill and how it would promote the balance the financial costs, limitations, and non- financial benefits of the process. This analysis shows that if production using 3D technologies is a legitimate goal, a centralized rapid production facility is significantly more efficient at the present time than a distributed shipboard maintenance based program. This is both because of the financial costs and because of the increased flexibility and scalability of a land-based facility.

The use of 3DS and 3DP in the way proposed in this scenario is essentially a rapid production facility. Rapid production was initially thought to need to be high-volume in order to be economically efficient (Bak, 2003). However, later research showed that low-volume job- based rapid production methods also were economically efficient, particularly due to the lack of need for complicated tooling procedures (Bassoli et al., 2007). SLA, the printing technique suggested for this facility, is ideal for the centralized rapid production facility because it minimizes skewing from stored plans (Melchels et al., 2010). Thus, the technical implementation is likely to be both efficient and effective.

Neither is rapid production limited to the materials that can be produced with a 3D printer (essentially polymers, metals, and composites). Instead, rapid casting procedures can create products from materials such as metals, glass, Styrofoam, or composite materials (Bassoli et al., 2007) as well as ceramics (Nan et al., 2011). This potential substantially increases the flexibility of the rapid production process. Although

this would be difficult to take advantage of in shipboard maintenance systems, it would not pose a problem in a land-based facility with room for raw materials.

The issue of economies of scale brought up by Bak (2003) would also offer less of a problem in a centralized facility that was providing parts for the entire fleet. The storage of plans is, as previously observed, less expensive than the storage of parts. Thus, by having a centralized library and production facility, it would be possible to maximize economies of scale by managing the type and numbers of products produced. The ability to use rapid casting or lost wax casting and multiple materials would also make it easier to plan production and manage quantities in order to distribute parts to the entire fleet.

This scenario also has long-term potential in terms of management of parts, in order to reduce the maintenance costs associated with the naval fleet. In particular, with cooperation with the design teams as discussed in the first scenario, the 3D design library could be established with both new and existing parts designs and specifications. New parts could be added as they are designed, while old parts could be added as they are requisitioned by maintenance engineers or on a planned schedule. In the long run, this would reduce the cost of maintenance by reducing the cost associated with obsolescent parts.

Using the centralized rather than distributed production approach is not without its costs. In particular, the main benefit of the distributed part is that it offers immediate or just-in-time supply of parts, especially in emergencies or in situations where parts are difficult to receive (such as on submarines). This centralized rapid production system, in contrast, would provide parts relatively rapidly but would still require normal lead times for supply chain distribution. This could increase the time associated with the production process to a few days, rather than immediately. However, the much lower cost and increased efficiency could mean that for all but extremely sensitive situations it would be appropriate for the short lag in the supply chain to remain in place.

The mild disadvantages of the centralized parts library and production system compared to the partially distributed system notwithstanding, it is clear that for rapid production this would be a better choice. It would maximize equipment utilization,

expand the range of materials and techniques that could be used for production, and maximize efficiency for parts that were required across the fleet. It would also maximize personnel efficiency, since it would allow for the appointment of a few highly trained and efficient technicians, rather than the training of a large number of technicians who will only use the 3D production technologies for a small portion of their work. It would probably take some time to build a complete parts library, but this should not be understood to be a negative factor, but simply an issue involved in the approach to 3D implementation. It would be particularly effective in conjunction with the design scenario, since then production facilities and designs could be shared and even combined. This would allow even greater efficiency maximization across the program.

F. SUMMARY

This chapter has discussed three scenarios for implementation of 3DS and 3DP technologies into the CPLM lifecycle, as based on the literature review and what it revealed about common usage situations for these technologies. These scenarios included the product design stage and use in construction of visual and functional prototypes; small-scale distributed manufacturing of rare parts or emergency replacements; and large-scale rapid manufacturing. Table 5 summarizes the scenarios and their costs and benefits.

The findings and discussion have shown that the most effective application is at the design stage, while the benefits of the rapid manufacturing stage may also be worthwhile. However, there is not as clear a case for the distributed shipboard mechanisms, meaning that there is not necessarily a desirable application for this situation. These findings were discussed in line with the literature and its findings within the CBA, showing how it agreed with or did not agree with previous findings. This showed that the Navy’s situation is largely consistent with the corporate environments and research environments that have previously been used for study. In the following chapter, the findings are summarized and the study is concluded.

	Scenario 1	Scenario 2	Scenario 3
Scenario description	Product design and development	Distributed small-scale production	Centralized large-scale rapid production
Configuration (Per installation)	1 3DS 2 printers No additional personnel	3DS + 3DP (per ship) 3D Library (12 scanners, printers, data storage, technicians)	12 3DS 3DP (manufacturing grade) 4 technicians
Total Costs (per installation)			
4-man team	$67,785		
6-man team	$70,185		
10-man team	$74,985		
Ship		$149,530	
3D Library		$5,091,535	275,515
Manufacturing Setup			2,000,000
Nonfinancial Costs/benefits	Efficiency improvement Rapid prototyping Increased development speed	Immediate part replacement Lowered shipboard parts inventory Obsolescence protection	Centralized production for parts replacement Obsolescence protection Longer service life Improved efficiency

Table 5. Analytical scenario summary

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V. RECOMMENDATIONS AND CONCLUSION

This chapter summarizes the findings of the research and provides general conclusions surrounding the findings and suitability of 3D technologies for SHIPMAIN. It then discusses the general recommendations for practice and areas for future research. Finally, it discusses the limitations of the study that need to be taken into account in order to apply the findings.

A. SUMMARY OF FINDINGS AND CONCLUSION

This research examined three distinct scenarios for the implementation of 3DS and 3DP technologies in the U.S. Navy's CPLM process. These scenarios were suggested by the existing secondary literature, which suggests a number of uses of 3D technologies in the design and manufacture of commercial products. The uses identified included: sharing information and rapid prototyping between designers of products; providing on-the-spot production capability for difficult to find parts; and providing centralized rapid production facilities on a large scale. The findings regarding each of these areas can be summarized as follows:

- Product design is a well-trodden area of 3D technology application, and it is one of the most beneficial applications. By enabling the use of 3DS and 3DP technologies, teams of designers at naval and supplier bases can exchange information, engage in reverse engineering, and rapidly produce design and functional prototypes, potentially reducing development and production periods by months. This is a highly beneficial application.
- The benefits of the shipboard maintenance application are not as clear. In theory, 3D technologies could be used to smooth production and supply difficulties as well as supply obsolete or rarely used parts, or provide emergency parts. However, in practice there are a number of difficulties found in this application. First, personnel would have to be trained and equipment distributed across the fleet for what would likely be a minority application, which would incur a substantial cost. Second, the materials and physical capabilities of 3D printers are still somewhat limited, although they are getting better. While producing polymer, composite, or some metal parts would not be difficult, there are many materials used onboard ship that are not available, and using investment casting would introduce a new level of difficulty.

- The 3D parts library and rapid manufacturing line introduced in the most expansive scenario is a much larger investment in time and personnel than the design scenario. However, it would have the benefit of being less expensive than the shipboard maintenance crew training scenario, since a relatively small number of personnel would be needed to maintain the library after its initial setup. Issues such as investment casting safety would not be as important in a land-based facility as in a shipboard facility, and more advanced training could be undertaken. It is also not unreasonable to suggest that ships could place orders that could be made rapidly, given the low tooling time and small-batch capacity of the rapid prototyping environment. This scenario is more expensive than the design scenario, but would provide many of the benefits of the shipboard scenario at lower cost.

Based on this assessment, 3DS and 3DP technologies do have benefits for the collaborative product development lifecycle, but these benefits are not spread evenly. In particular, the further the solution moves from small-scale and centralized teams, the less efficient it becomes in its use of the 3DS and 3DP technologies. This suggests that at least for the initial implementation of 3D technologies, small-scale and centralized teams should be used to determine the true cost of the program and identify its benefits (if any) that go beyond this analysis. This study is not comprehensive and does not examine all existing technologies. However, these technologies change rapidly in any case, suggesting that by the time this study is slated for implementation it could have become obsolete. Instead, the focus is on identifying general information about 3D technologies and determining in what stages of the product development lifecycle it could become most useful. In this respect, it has been successful at illuminating both the costs and the benefits of the technology and how it can be developed over time.

B. RECOMMENDATIONS FOR PRACTICE

The main recommendation for practice in this research is that the use of 3D technologies should be focused on the product design stage at this time, with a potential development of a 3D technology library and centralized rapid production line for unusual parts. The benefits of 3DS and 3DP technologies for product design are well-established, and the personnel requirements of the design stage are also likely to be much easier to meet than the requirements for other environments. As the smallest in scale of the three proposals, this would also offer the opportunity to develop a proof of concept related to

the utility of the 3D technology prior to the more widespread implementation. The use of a central 3D library and rapid prototyping facility would also be effective in that it would help meet the needs of an aging fleet and offer a way to supply obsolete or unusual parts without the extensive personnel requirements of the shipboard program. While it would lose some benefits of immediacy, its cost would be much lower. The shipboard program, while appealing in theory and potentially having a high benefit, has a number of disadvantages, including high personnel costs and training costs that make it infeasible at the present time. Thus, this is not recommended as an approach right now, although it could be implemented later if equipment costs and increase in skilled personnel allow. For the present time, the balance between cost and benefit suggests the minor delay in transporting parts from a central rapid manufacturing facility is less of a cost than the high implementation costs of the shipboard program.

C. AREAS FOR FUTURE RESEARCH

One of the most pressing issues for the SHIPMAIN program is maintenance of older ship designs or unique or rare parts and assemblages, which can be problematic for collaborative supply chain management. However, it is uncertain how much difficulty these parts pose or what the challenges are in supplying them. Future research should concentrate on identifying the specific challenges involved in supply chain management of unusual parts, including identifying the precise frequency of availability shortages and the cost of supply. This would provide more robust information that could provide a better basis for estimation of the relative costs and benefits of using 3D technologies onboard ship as a means of easing supply issues. Continuing research and environmental scanning directed to identifying the improvements in 3D technology, particularly when it comes to materials that can be deposited, would also offer more information about when (if ever) the use of 3D technologies in immediate supply line situations would become beneficial.

D. LIMITATIONS OF THE STUDY

The main limitation that needs to be considered in this study is the secondary nature of the findings. Because it was constructed based on a series of hypothetical case

studies, it reflects a general finding regarding the application of the 3DS and 3DP technologies currently available to the SHIPMAIN program and the CPLM system currently in use, rather than specific findings. These findings would need to be more rigorously assessed using actual figures from the programs in order to be applied in practice, given that there are still concerns regarding the utilization of 3D technology. The findings are also limited in that they did not take into account the requirements for increased human resources capacity, including potential changes in the recruiting system needed to support the increased use of 3D technologies onboard ship and in other situations where there may not currently be substantial technology support. These are also issues that need to be taken into account when applying the practical findings of the study to the CPLM system.

These limitations have arisen because of the secondary and theoretical nature of the research design. This research design was required due to several concerns, including time and resource limitations and limitations on availability of information. It is based on reliable information including up-to-date costings from 3D technology suppliers, which offers substantial strength. However, its weakness is that it is not based on reliable estimates for program needs, but rather instead relies on general information about the program. This is something that the researcher would remedy in future research designs if possible.

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